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PRELIMINARY REPORT

DEVELOPMENT OF

ELECTROSTATICALLY SUPPORTED GYRO

IDM REPORT NO. 3943-1

By

Albert S. Cahn

March 3, 1956

ABSTRACT

The purpose of this project is to create a navigational reference device similar to a gyro, but orders of magnitude superior in accuracy and stability. The fundamental theoretical analysis is presented in the Appendix. The main body of effort of the project is to furnish physical proof of the theory presented.

Briefly, the principle is as follows: A small, hollow aluminum sphere, with an attached disc (the planet Saturn and its rings exemplifies the shape) is suspended in an electrostatic field (the whole assembly contained in a vacuum). The field supports the rotor in three dimensions. The rotor is spun, by an externally applied electromagnetic field, at a speed of approximately 80,000 rpm, and because it is in a high vacuum, continues at this speed after the rotating magnetic field is removed. The orientation of the rotor is then "sensed" by electrodes positioned near the disc, or ring.

The major segments of the work which have been accomplished:

A rotor has been fabricated, electrostatically suspended in one dimension, and spun on an experimental basis.

The techniques for fabricating the rotor, the vacuum envelope, and the suspension electrodes (to the required accuracy) have been examined and defined.

The techniques of suspension and position sensing have been proved, and are being improved.

The major work remaining is to complete the fabrication and assembly of the components, to suspend the rotor in three dimensions, spin it, and examine the accuracy and stability of the resultant device.

Electrostatically Supported Gyro
IDM Report No. 3943-1

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1.0 INTRODUCTION

On the 1st of November, 1954, Instrument Development & Mfg. Corp. was notified by the Office of Naval Research that it had been awarded a contract for research on the design and development of an electrostatic gyro instrument. The work, as specified by the contract, stated that Instrument Development & Mfg. Corp. should:

1. Design, develop and construct an electrostatically suspended gyro rotor instrument with associated necessary control and sensing instruments;
2. Design, develop and construct a free gyro clock instrument for the purpose of employing an electrostatically suspended gyro rotor as an inertial axis reference device; and
3. Explore and develop the inertial reference capabilities of the instrument constructed in paragraph 2 above. Specifically to:
   (a) Make detailed measurements of drift rate of the gyro instrument;
   (b) Make adjustments to minimize the drift rate of the gyro;
   (c) Explore the dependence of the gyro axis stability on its physical orientation; and
   (d) Conduct such other tests as to deviate from the

requirements of (a) through (c) above, subject to directions from the Scientific Officer.

This contract resulted from a proposal submitted June 24, 1954, based upon a theoretical analysis by Dr. Arnold Nordsieck of the value of an electrostatically supported gyro to a free inertial navigation system and the difficulties inherent in its fabrication. Since Dr. Nordsieck's report was submitted as an appendix to Instrument Development & Mfg. Corp's proposal, but was never issued as a separate report, it is hereby included as an appendix to this report for the sake of completeness. For the remaining portions of this paper, we will assume that the reader is familiar with Dr. Nordsieck's study.

2.0 INITIAL CONCEPT OF TASKS TO BE ACCOMPLISHED

As a starting point for the research and development work of this contract, it was decided to commence construction of a gyro instrument along the general lines described in Dr. Nordsieck's paper. That is, it was felt that as a starting point we would endeavor to build an electrostatically supported gyro with the physical dimensions suggested by Dr. Nordsieck and to use his suggestions for an envelope made of glass with deposited electrodes, placed as he suggested them in Figure 2 of his paper. Likewise, we decided to use the general concepts for electronic circuitry which he suggested and to see what flaws and improvements we could discover.

3.0 PRELIMINARY EXPERIMENTS

Before any design could be frozen for the construction of the gyro, it was necessary to make certain preliminary investigations to determine what materials to use and what techniques would work in order to carry out the actual construction.

3.1 INVESTIGATION OF MATERIALS

First of all we needed to construct the rotor out of a material with a high strength to weight ratio. This requirement seemed to indicate that the most promising substances were aluminum and titanium alloys. Aluminum had the advantage of being well understood metallurgically and easy to machine. However, titanium seemed much more advantageous in view of its known behavior in closed off vacuum systems.

We decided to make a twofold investigation in order to gain time. We began experimenting with a piece of titanium alloy No. MST 6Al-4V to see whether or not we could successfully machine a rotor from this. Simultaneously we began experimenting with aluminum alloy No. 75ST-6 to see whether or not it would be possible to seal off a vacuum including a piece of this metal without heating the system excessively.

It actually turned out that both problems could be overcome successfully. It was our experience that by

exercising care in machining, and taking very small cuts, that we were able to fabricate a titanium rotor to the required tolerance. Also, we were able to achieve a satisfactory sealed off vacuum containing a piece of aluminum alloy. Since we finally decided to use an aluminum rotor, our method of achieving this sealed off vacuum is appropriately described here:

(a) All the glassware for the vacuum chamber was washed in a 10% solution of hydrofluoric acid for 60 seconds, washed in tap water for five minutes and finally rinsed in hot distilled water and oven dried at 100°C.

(b) Aluminum disc was dipped quickly in a 10% solution of sodium hydroxide and rinsed in tap and hot distilled water to clean the surface.

(c) Aluminum disc was inserted into glass chamber and sealed.

(d) Getter assembly chamber was made and sealed to disc chamber. Getters used were from King Laboratories, 127 Solar Street, Syracuse 3, New York, Identification No. 1943-1-SS-d embedded getter with 9 Barex No. M-411-B 20 milligram pellets.

(e) Ionization gauge (RCA No. 1949) was sealed to above chamber manifold.

(f) Entire assembly was sealed to vacuum system and baked for 24 hours at 225°F.

(g) Assembly was cooled to room temperature and RCA ion gauge was outgassed by internal bombardment. After outgassing, pressure was recorded at 10^{-6} mm Hg.

(h) Getter was flashed slightly on pumps to outgas.

(i) Pressure was increased when getter was flashed to 10^{-3} mm Hg and slowly returned to 10^{-6} mm Hg. Periodic slight flashing of getter was continued until it was accompanied by very little pressure rise.

(j) Getter flashed completely.

(k) Complete assembly was sealed off from system.

The decision to use aluminum rather than titanium came about much later in our program and was really decided upon because of an unforeseen effect due to the high resistivity of titanium alloy. Our plans have always been to spin the rotor inductively and a calculation by Dr. Nordsieck, using the resistivity of aluminum, showed that a rotating magnetic field of approximately 30 gauss would satisfactorily accelerate a rotor of the dimensions we planned. The Chemical Handbook lists the resistivity of titanium as being 3.2×10^{-6} as opposed to the resistivity of 2.828×10^{-6} for aluminum and

without investigating further we concluded that we would be able to spin a titanium rotor inductively as satisfactorily as we could an aluminum rotor. However, commercially available titanium alloys we found have resistivity of approximately 150×10^{-6} and resistivity of this magnitude would have called for an entire redesign of the starting coil system. Since we had learned that aluminum could be successfully outgassed, we decided to proceed with an aluminum rotor.

3.2 VOLTAGE BREAKDOWN FROM EVAPORATED ELECTRODES

One of the first facts which we felt that we needed to know was what voltage could be placed on evaporated electrodes without breakdown. In order to levitate a rotor of the weight and dimensions proposed by Dr. Nordsieck's study, calculations indicated that approximately 10,000 volts were needed to be placed on the supporting electrodes. If it turned out that excessively high field intensities were caused by these voltages at the edges of the extremely thin evaporated electrodes, then we would be forced to design an electrode system other than the apparently convenient one of evaporated electrodes on a polished glass surface.

To determine this we evaporated nichrome electrodes of the shape shown in Figure 1 on a flat piece of glass and painted conducting strips of silver paint to the

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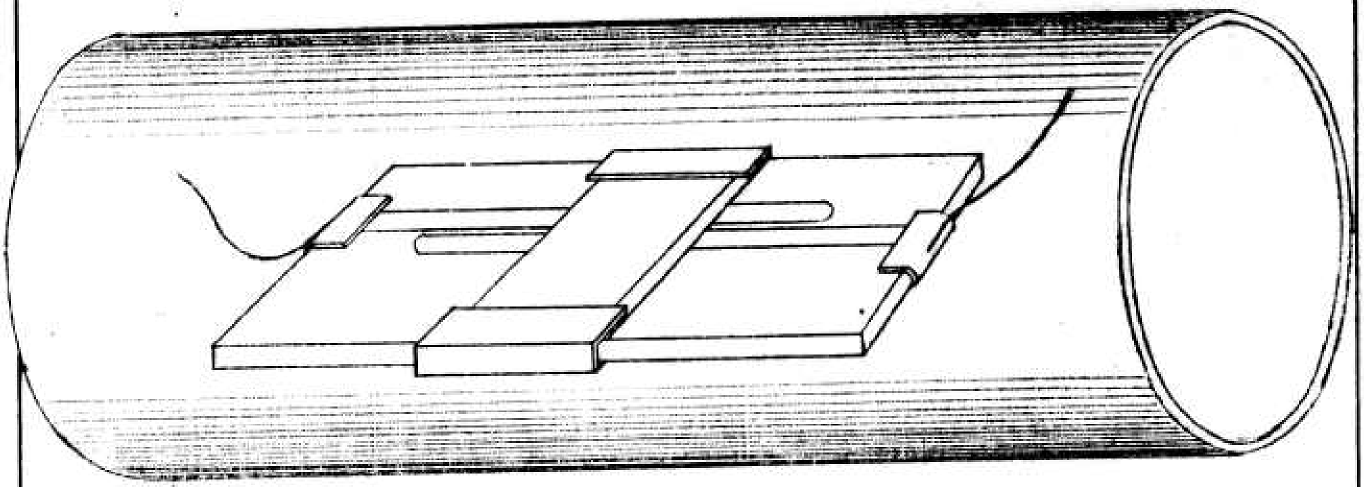

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HIGH VOLTAGE ARC TEST FIXTURE

FIG. 1

edge of the glass to which wires could be fastened by spring loaded clips. This size and shape of electrode was chosen since the edges facing each other were the same distance apart and approximately the same length as the proposed ring electrode around the polar caps as are shown in Dr. Nordsieck's paper. These electrodes were also approximately the same area as the actual electrodes we proposed to use. A piece of aluminum was machined so that it could be clamped to this glass, distant from the electrodes by .015". This was our proposed clearance between the rotor and the electrodes of the envelope so that this mockup furnished a good approximation of the physical situation which would occur if a rotor were actually levitated.

This entire assembly was sealed in a large glass tube with sealed wires leading through to the electrodes and the system was evacuated to less than 10^{-6} mm Hg. The voltage on the electrodes was gradually increased. Some sparking began to occur at approximately 5,000 volts and seemed to be connected with cleanup of the electrode surfaces. Sparking continued sporadically until we reached approximately 8,500 volts at which point it seemed to be fairly continuous. Later microscopic examination of the electrode surfaces showed them to be deeply pitted and scarred by the sparking so that we

were fearful that the plan to use evaporated electrodes would not be satisfactory.

After discussion with a number of experts in this field, we reached the conclusion that the electrical behavior of the evaporated electrodes was a function of the condition of that surface more than anything else and that perhaps we had not been sufficiently immaculate in putting together the first experiment. We consequently repeated the experiment using extreme care to see that all surfaces were well cleaned and outgassed before any potential was applied. This time we were able to put 12,000 volts without any sparking and examination of the electrodes showed no deterioration whatsoever. At a later experiment we managed to put 14,000 volts on the electrodes before breakdown. We consequently decided that the evaporated electrode system was feasible and have continued under that assumption.

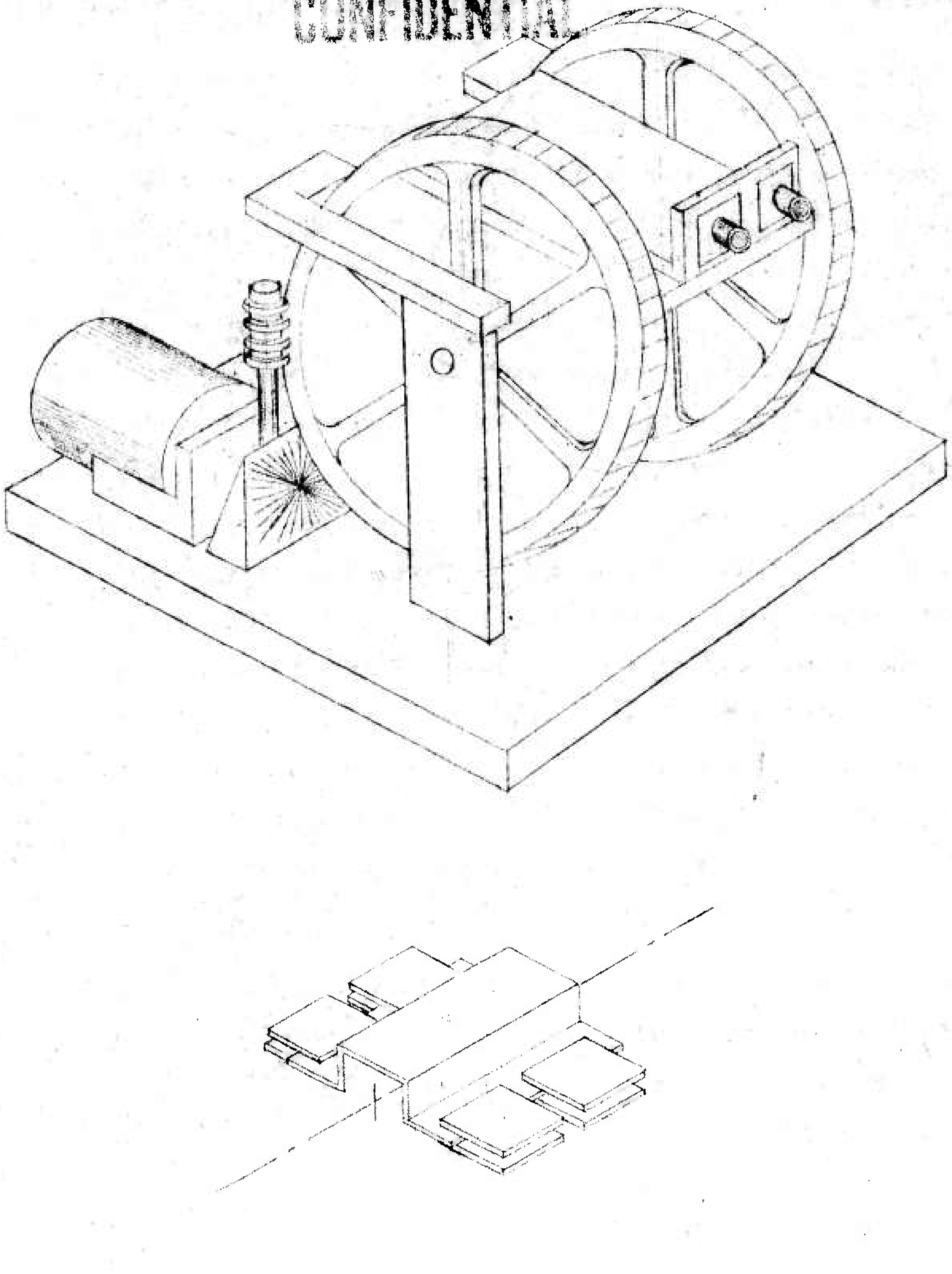
3.3 DETECTION OF MOTION BY MEANS OF CAPACITANCE BRIDGE

Dr. Nordsieck's report proposed that the aspect of the rotor be determined by utilizing the unbalance in a capacitance bridge, resulting from the mechanical motion of the rotor. This unbalance was to be caused by the motion of the rim of the rotor and would yield two signals (one for motion of the rotor axis in each of two normal reference directions). It was planned to use the

signals from this unbalance to mechanically orient the envelope so that the envelope would follow the aspect of the rotor with an error of less than 10 seconds of arc. Dr. Nordsieck's calculations show that maintaining the aspect of the envelope to that of the rotor to this small angle is necessary in order to avoid undesirable extraneous torques. Likewise it was planned to utilize the aspect of the envelope as an indication of the rotor axis orientation.

In order to test the feasibility of this scheme, a mechanical model was prepared with a cylinder containing two side flanges (see Figure 2) constrained to turn about a common axis with a dielectric holding four electrodes. This furnished a one dimensional analogue of the rotor and is essentially what would be obtained if a cross section were cut through the center of the rotor along its axis of symmetry and forming a right cylinder with this cross section. The electrodes were made the same area as was planned for the envelope; the spacing between the electrodes and the rotor counterpart is .015", the clearance planned to be used between the rotor and the envelope.

The rotor counterpart and the following electrodes were each driven independently by identical servo motors, geared to reduction of 16,000 to 1. Both motors were



TILT CIRCUIT TEST FIXTURE

FIG. 2

mounted side by side and equipped with pointers so that the lag of one motor behind the other could be readily observed. The motor driving the rotor counterpart was controlled by a rheostat; the motor driving the electrode assem y was driven by the servo system shown in block diagram, Figure No. 26. Figure No. 27 shows the electrical circuitry involved. (See pages 53 and 55.)

It turned out that the electrode driving servo-controlled motor followed the independent rotor-driving motor to better than 30 degrees. Through our gear reduction, this corresponded to a difference between the aspect of the rotor and that of the envelope of 7 seconds of arc, or corresponded to a linear motion of the edge of the rotor flange of approximately .00003". The successful accomplishment of this experiment confirmed our belief that it is feasible to use this method for driving an envelope to follow the aspect of the rotor.

3.4 EXPERIMENTS TO DETERMINE STABILITY OF LIFTING CIRCUITS

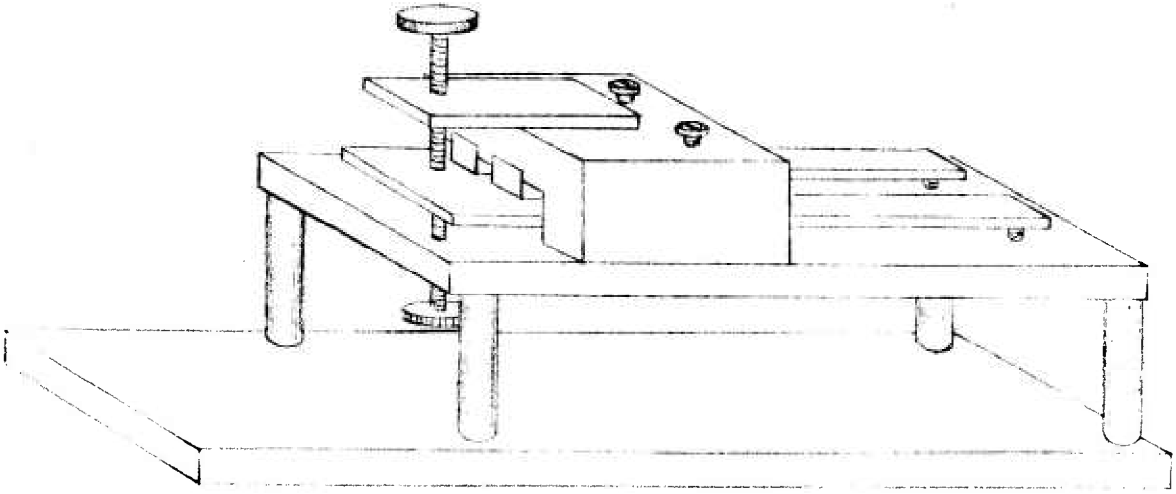
Since the concept of utilizing an electrostatically supported gyro depends altogether on being able to support a weight of several grams by servoed electrostatic attraction, we felt that it was prudent to attempt this in one dimension as soon as possible.

Our original idea was to fabricate a flat plate hinged at one end so that it would be able to move only

in one direction. The other end of the plate was to be suspended between two sets of electrodes (see Figure 3). These electrodes were made the same area as those proposed in the gyro and the spacing between them and the flat plate was .015", the clearance distance contemplated in the gyro. The front end of the plate was fitted with a microfilm of a linear rule so that a 150 power microscope would be able to detect motions of approximately .00001".

It was necessary to perform this experiment in vacuum in order to avoid high voltage discharge. Our scheme was to place the model on the plate of our vacuum system; to enclose the model with a cadmium plated steel cylinder some 12" in diameter, and to cover the steel cylinder with a piece of 1/2" plate glass. Rubber"O" rings were used between the glass and cylinder and between the cylinder and the plate of the vacuum system. A mirror and lens system within the vacuum chamber allowed a microscope on the top of the glass to be focused on the microfilm so that motion of plate could be observed.

Unfortunately, we were not able to achieve sufficient vacuum in the near neighborhood of the model to successfully maintain the 10,000 volts required without sparking. Consequently, no information was derived from the experiment.



We worried that this local high pressure might be inherent in the geometry of the model and be caused by the small clearance which existed between the electrodes and the hinged plate. The ion gauge of the vacuum system (which was at some distance down the vacuum line towards the pump from the model) showed a vacuum of better than 10^{-6} mm Hg and from our earlier experiment with evaporated electrodes, we felt confident that these electrodes should be able to hold 10,000 volts without sparking. The earlier electrode experiment had also had a small crevice (although not as extensive) and this had not interferred with the maintenance of high voltages upon the electrodes. We finally came to the conclusion that the organic material, which we had used as a dielectric support for the electrodes, was continuing to outgas at a sufficient rate so that there was local high pressure in the vicinity of the electrodes and that this was the cause of the sparking. We consequently decided that we needed to construct a one dimensional model entirely from metal and glass in order to test the lifting circuit.

By this time we had successfully fabricated a rotor and it occurred to us that a more realistic model could be devised by utilizing a rotor constrained to slide upon a glass rod and by fashioning solid strips of aluminum in the configuration of the polar electrodes which we planned to use in the gyro. Glass spacers

were used to maintain the distances between the electrodes and small teflon washers were used to keep the rotor from coming in contact with the electrodes when no lifting voltages were being applied (see Figure 4).

This model had the advantage that it could be operated in a bell jar since the motion of the rotor could be observed from the side. We decided that it was unnecessary to attempt to observe this motion with a microscope since the error signal is a far more sensitive indication of motion of the rotor than can be seen by a microscope.

This experiment turned out successfully and we were able to levitate the gyro. This model has proven quite useful, and we have maintained it for the experimentation necessary during the course of further development of the holding circuitry.

3.5 EXPERIMENTS IN USE OF INDUCTION COILS TO SPIN ROTOR

Dr. Nordsieck proposed to operate the gyro by placing the rotor, while electrostatically supported, in a rapidly rotating magnetic field until the rotor was spinning with sufficient angular velocity. At this time the field was to be removed and the rotor allowed to coast. The field strength required is quite simple to calculate; however, we felt that it was worthwhile to spin a rotor experimentally. This experiment was done in a straightforward manner. A rotor was mounted on a

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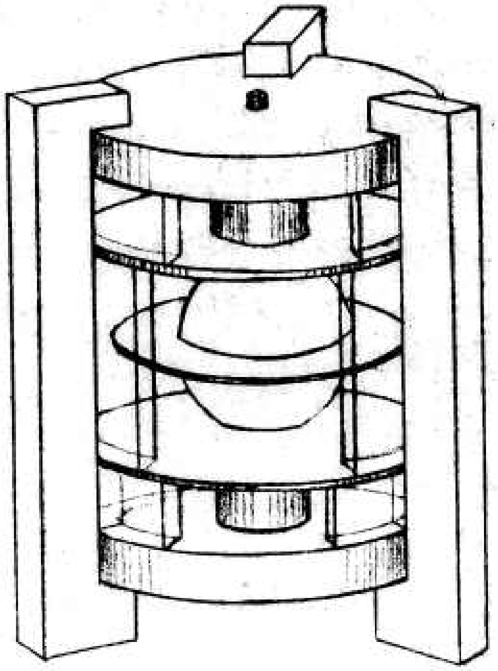

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ROTOR HOLDING CIRCUIT FIXTURE

FIG 4

steel shaft held by a "U" shaped piece of lucite and two coils of copper wire were wrapped around the entire system (see Figure 5). The angular velocity of the rotor was determined by a strobotac.

Dr. Nordsieck calculated that approximately 80 ampere turns were required to achieve the acceleration desired for the geometry we were contemplating. This amount of current was placed in the coils by means of the circuit shown in the wiring diagram (see Figure 6). The acceleration seemed to us quite satisfactory (100 revolutions per second per minute). In a vacuum this would achieve an angular velocity of 80,000 revolutions per minute in less than 15 minutes. This was proposed by Dr. Nordsieck as a reasonable length of time for the startup of the rotor.

We performed one other experiment with the starting coils. During the course of development it was decided that the envelope would be sealed with a heavy ring of kovar around the outside of the envelope. We feared that inductive heating in this kovar ring during startup might crack the glass-to-kovar seal. To test this point, we wrapped the starting coils about a mockup of the envelope and turned on the power that would be used in starting the rotor. A thermocouple was fastened securely to the metal portion of the envelope so that the tempera-

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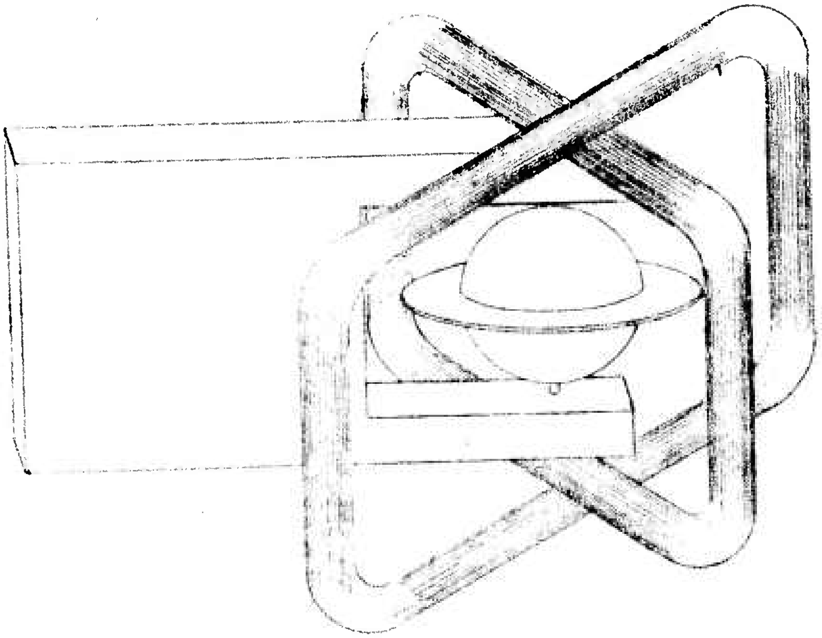
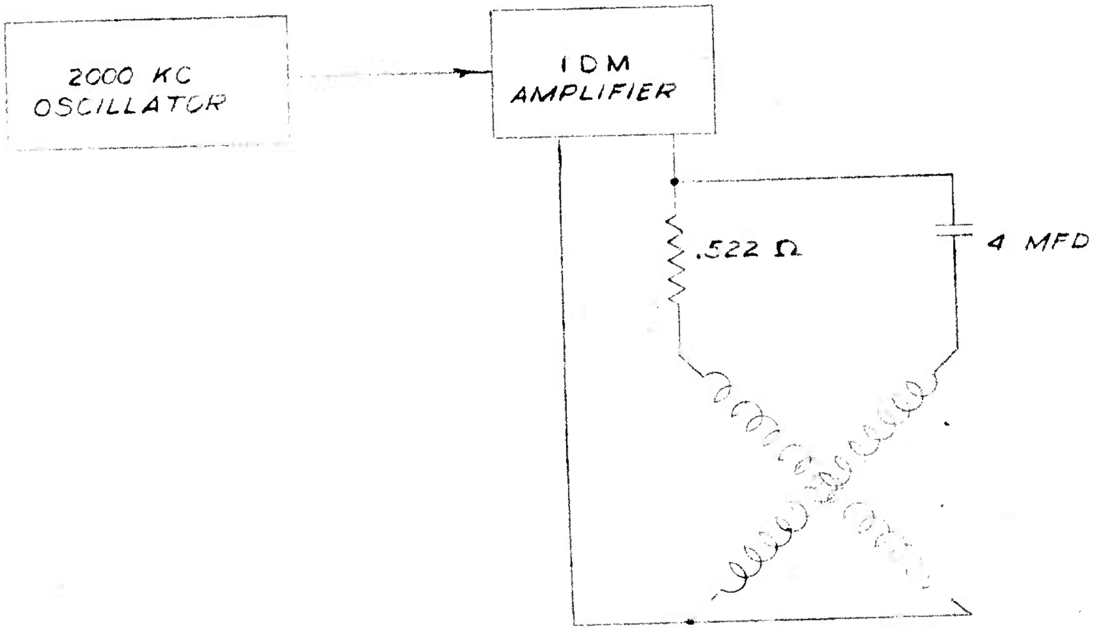


ACCELERATION COILS & ROTOR FIGURE 5



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WIRING DIAGRAM STARTING COIL	FIG 6

ture could be observed. As we feared, after a very few minutes of operation, the temperature of the kovar ring rose to 85°C, which we felt was too high for safety to the glass-to-kovar seal. However, by blowing a forced draft over the kovar ring, the temperature at all times stayed below 25°C, which we feel is completely safe. Consequently in the operation of the final assembly of the gyro, we plan to air cool the instrument during startup time. Still further reduction of temperature could be achieved by wrapping copper coils around the kovar ring and running water through these. However, there is no indication that this is necessary.

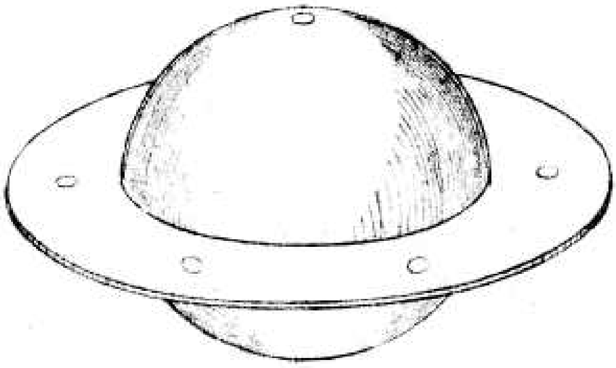
4.0 FABRICATION OF THE GYRO ELEMENTS

4.1 FABRICATION OF THE ROTOR

The final design of the rotor is shown in Figure 7.

As mentioned in an earlier section, the decision was made to use 75ST-6 as being the best aluminum alloy, primarily because of high tensile strength. We ran physical tests upon samples of the aluminum alloy we had at hand to determine the actual tensile strength of this material rather than assume that the tensile strength was that quoted in the handbooks. We likewise wished to determine the effect of different heat treatments upon the aluminum used.

We prepared a set of ten test bars, all of which



ROTOR DESIGN FIG. 7

were heat-treated by soaking them in molten salt at a temperature of 870°F for a period of one hour, followed by a water quench. One test bar was then brought to the T-6 condition by heating it in air at 250°F for twenty-four hours, the recommended aging treatment. A set of eight other test bars were aged by bringing them respectively to 400 and 500°F for a period of twenty-four, forty-eight, seventy-two and ninety-six hours. After this we measured the yield point and tensile strength of the ten bars by means of an extensometer. The result of these measurements are shown in Table No. I.

TABLE I

Aging Temperature °F	Aging Time Hours	Yield Point (P.S.I.)	Tensile Strength (P.S.I.)	Elongation %
(no aging)		51706	77177	17.5
250	24	73357	82781	14.0
400	24	31441	48568	15.5
400	48	26999	44574	16.5
400	72	24707	42027	16.5
400	96	24028	41666	17.0
500	24	20449	38854	18.5
500	48	18660	36809	19.5
500	72	18404	36298	19.5
500	96	16871	35531	19.0

We experimented a great deal in order to find what we felt were the proper techniques for machining the rotor. Later, we spent much time building the tooling and gauges necessary to fabricate this piece to the required tolerances. The procedure finally developed,

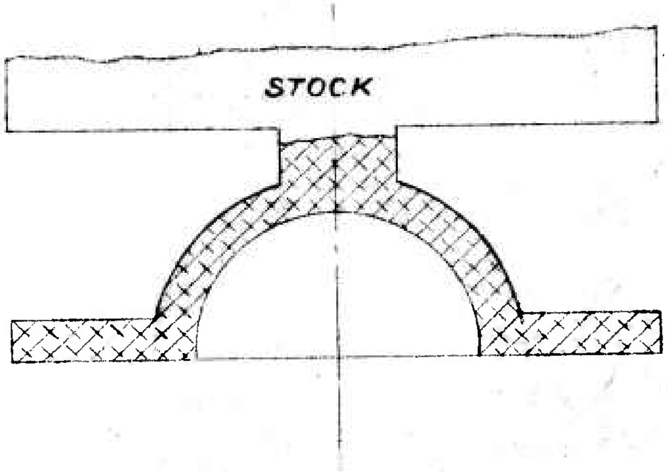
which seems to be completely satisfactory, is as follows:

(a) A rough blank of the rotor of the dimensions shown in Figure 8 is first formed using certain rough-form tools developed for this work. This piece is then parted from the bar stock, and solution heat treated by immersion in molten salt at 870°F for a period of thirty minutes, followed by a water quench.

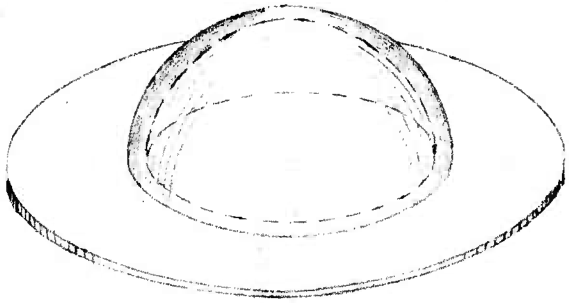
(b) Following heat treatment, the rotor blanks are rough machined to the dimensions shown in Figure 9 so that the blank now fits into a special fixture (IDM T258) for holding during the finish of the inside surface.

(c) After operation (b) the part is waxed into the holding fixture and the inside surface and face are finished and inspected.

(d) The part is then placed in a lathe fixture (IDM T257) and the outside spherical surface is formed by a special radius fixture (IDM T255). While in this same fixture the outside flange surface and the step on the outside flange face are finished. Before the fixtures are removed from the lathe, the rotor halves are inspected by means of spherical gauges and special inspection fixtures which allow gauging



FIRST ROUGH ROTOR BLANK FIGURE 8.



SECOND ROUGH ROTOR BLANK FIGURE 9.

the work to ±.00005". When all surfaces are finished to the required accuracy, the work is held against the lathe fixture by means of a live center (IDM T262); the flange is parted, and brought to the required size.

(e) After the rotor halves are prepared as described above, rivet holes are drilled into the flange by means of a special holding fixture (IDM T168) and a special drill (IDM T167). The holding fixture clamps the rotor half very securely in place and is bolted to a dividing head of a milling machine. The special drill has a countersink attached so that by using this in connection with a dial indicator on the mill, one may very exactly face 8 holes around the rotor flange, each with an identical countersunk hole.

(f) The rivets are formed by carefully machining small cylinders of exactly the diameter of the hole and of the exact length required to go through the two halves of the rotor.

(g) Before riveting the two halves of the rotor together, it is necessary to clean and outgas the surface carefully so that trouble will not develop during final evacuation of the complete assembly. It is necessary to follow the procedure suggested in Section 3.1 of this report. The parts should be very

briefly dipped in a 10% solution of sodium hydroxide, followed by a rinse in tap water and then in boiling distilled water. After this they should be immersed in reagent acetone and left until they can be placed in a vacuum system. During this process they must be handled only by tweezers and never touched or brought into contact with metal that has not been recently washed with reagent acetone.

(h) The washed and cleaned halves and rivets should then be placed in the vacuum chamber. When the pressure has been lowered to approximately 10^{-3} mm Hg, they should be subjected to a glow discharge. The pressure should then be lowered to less than 10^{-6} mm Hg and the parts heated for twenty-four hours at a temperature of 150°F. Following this the parts should be brought down to atmospheric pressure in hydrogen.

(i) After the rotor halves and rivets have been treated as described in steps (g) and (h), the two halves are riveted together, making use of a special holding fixture (IADMT 254). Extreme care must be exercised during riveting to be immaculate and not allow any grease or oil to contaminate the rotor parts. Following riveting the rotors should be placed in a dessicating jar until finally assembled

in the gyro envelope, in order to keep them free from moisture and contamination.

4.2 FABRICATION OF THE ENVELOPE

The design of the envelope is shown in Figure 10. Early in our investigation, we believed that the best method of constructing the glass envelope was to blow glass blanks in the approximate form of a rotor half and to seal kovar wires in such locations that the various wires would each make contact with an evaporated electrode after the envelope was finished. We planned to grind and polish these blanks to the required internal dimensions, evaporate on the electrodes, and then cement the two glass halves together to form the final assembly. We planned to use, in lieu of the wires running to the polar cap electrode, a small kovar tube which could serve the double purpose of being an electrical conductor and a tube through which the assembly could be evacuated.

An early trial demonstrated that it was possible to grind and polish a piece of Corning No. 7042 glass with kovar wire or tubing sealed to the glass. This ground and polished surface was extremely smooth, showing no irregularities whatsoever between the surface of the glass and that of the kovar.

However, we found no acceptable way to grind and

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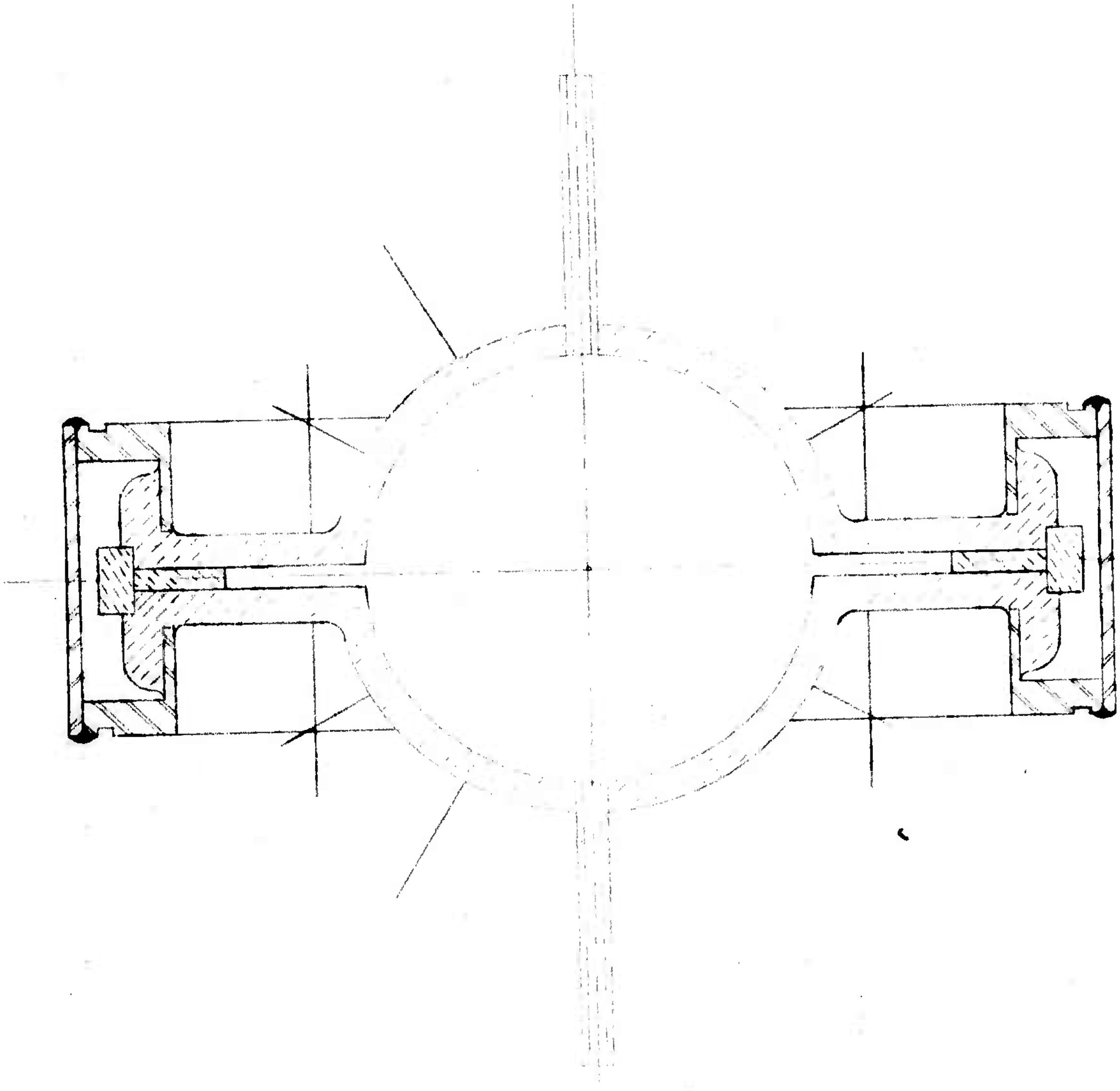

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GLASS ENVELOPE DESIGN

FIG 10

polish glass blanks which would meet the geometric requirements imposed by the shape of the rotor. The difficulties were caused by wanting to sink into the glass a flat section that would be opposite the flange of the rotor. There is no difficulty in grinding and polishing a flat surface with a semi-spherical cavity as we require, but to set this further in, as is shown in Figure 11, makes the task very difficult.

We decided to obviate this difficulty by using a separate glass ring as a spacer. The alignment of the two opposite envelope halves was established by an additional glass ring fitted to a diameter on the glass face, ground concentric with the spherical cavity. The proper orientation of the electrode patterns was maintained by a glass key fitted to ground slots in the outer alignment ring and also in the face of each envelope half. (See Figure 12)

We encountered difficulty in trying to devise a method of fastening the different sections of the envelope together that was suitable for the maintenance of a hard, sealed-off vacuum. Organic cements continue to outgas in a vacuum. Silver chloride or high lead content glass seemed possibilities for sealing the parts of the envelope together, but we were afraid that the

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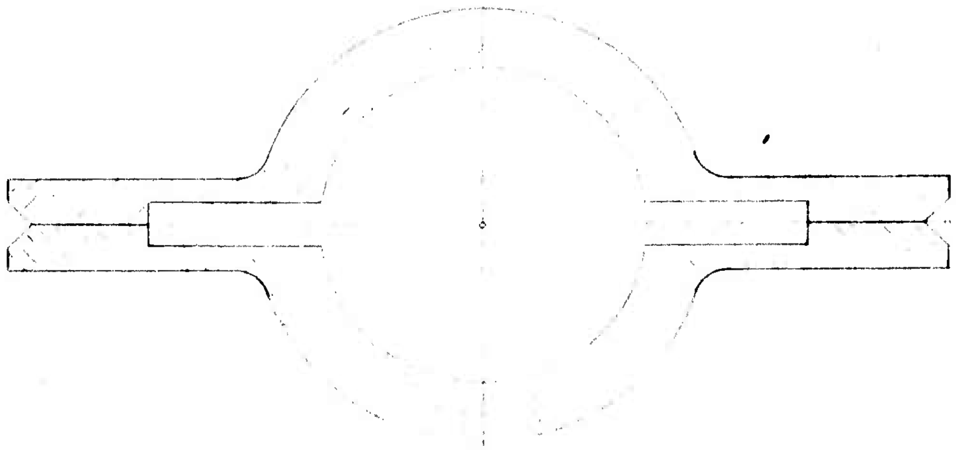
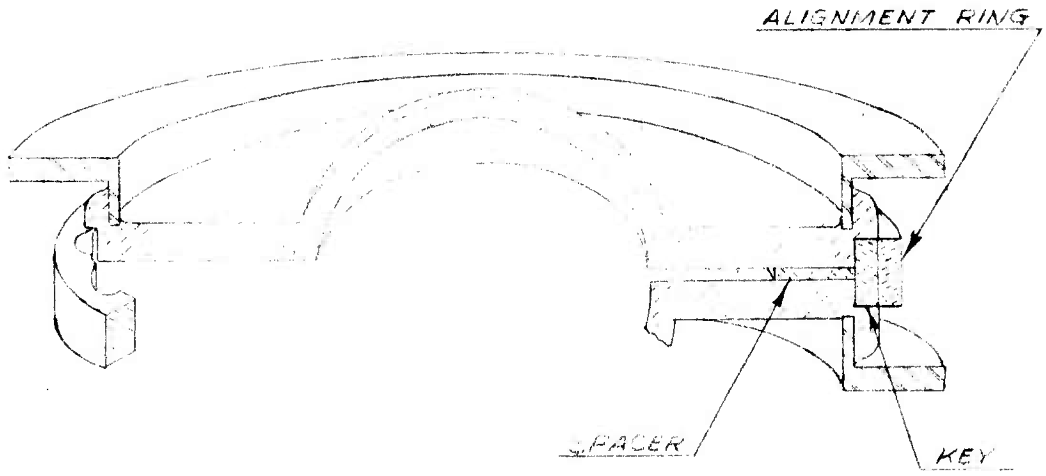


EARLY ENVELOPE PLAN FIGURE 11



LATER ENVELOPE PLAN FIGURE 12

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temperatures required might cause distortion of the internal envelope surfaces, or might affect the strength of the aluminum rotor.

After consulting with several firms who seemed skilled in such matters, we finally decided upon sealing a kovar ring to the glass envelope half in the manner shown in Figure 10 and heliarcing both halves to a piece of kovar tubing. The kovar rings are formed by copper brazing a short length of kovar tubing to a kovar ring cut from a piece of flat .100" sheet stock.

Kovar copper brazes extremely well in a hydrogen atmosphere. However, before sealing the glass to the ring, it is important to remove the excess copper so that it does not get under the glass seal. A small amount of copper beneath the glass seal would not seem to be particularly harmful, but the required acid cleaning of the kovar after forming the glass seal damages the seal by attacking the copper underneath the glass.

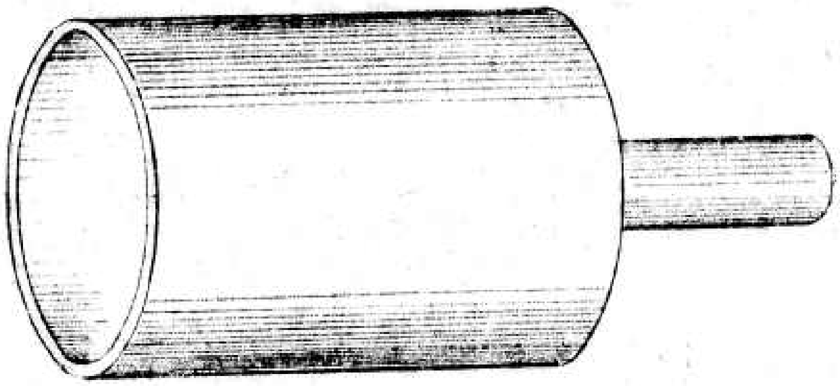
We performed a great deal of experimentation before learning a satisfactory method to seal the kovar lead wires through the envelope. We needed these placed with relative accuracy. Conventional methods of holding the lead wires seemed to be cumbersome and to rob sufficient heat from the glass so that irregularly shaped globs of

glass were left around the lead wires. It was difficult to grind these away and leave the envelope comparatively strain free.

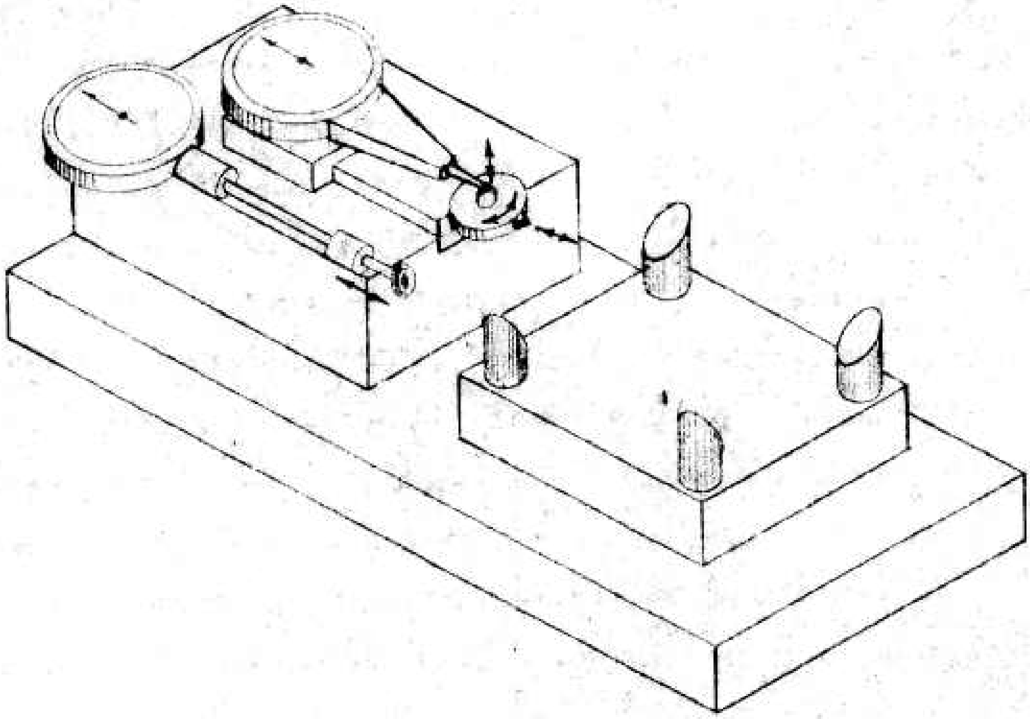
We finally hit upon a method of punching a small hole through the glass by a piece of white-hot tungsten wire and then sealing a piece of kovar wire, which had previously been coated with glass, into this hole. This required a fairly elaborate piece of tooling, which would first punch the holes in the required spots and which would then hold the kovar wires while they were being sealed.

For grinding and polishing, a special fixture was made to facilitate maintaining proper measurements in the grinding operation and also to be used to the best advantage for the final checking of concentricities and dimensions with the special inspection fixture. (See Figures 13 and 14)

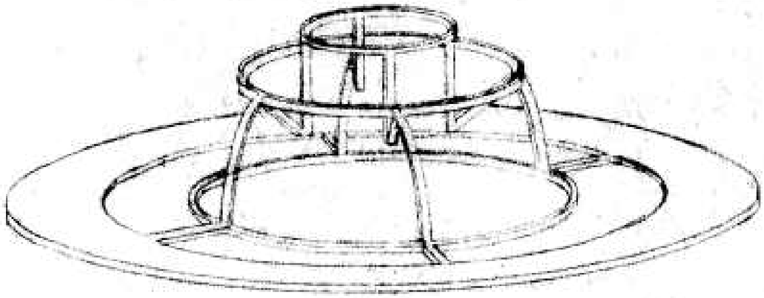
For the evaporation of the electrodes we machined the mask shown in Figure 15. We had first thought that to obtain the electrode pattern required by our geometry, it would be necessary to rotate the envelope halves while the electrode evaporation was taking place. However, an experiment showed that a mask of the shape shown would allow the electrode deposition quite nicely



ENVELOPE HOLDING FIXTURE FIG. 13



INSPECTION FIXTURE FIGURE 14



EVAPORATION MASK FIGURE 15

if the evaporated material were put in two long line sources.

For fastening the two envelope halves together, we were convinced that we would need some automatic welding machinery; since it seemed unwise to trust so delicate an operation to an operator holding a torch by hand.

Since no heavy walled kovar tubing of the required size was available, we were forced to fabricate this item by rolling a piece of heavy (.100") flat kovar sheet stock into a cylinder of the proper dimensions, and then heliarcing a seam along the length of this tube. This did not present any great technical difficulty except that the kovar requires an exceptionally heavy backing of inert gas during the welding process. After forming the piece of kovar tubing in this manner, we carefully ground the interior surface by means of a tool post grinder to a high degree of smoothness and roundness.

Experimentation demonstrated that it is possible to heliarc the kovar rings of the envelope halves to the outer cylinder without cracking the glass by fastening copper cold bars to the kovar parts approximately 1/4" from where the weld is taking place and by keeping water in the outer portion of the envelope so that there is no

unequal heating of the glass and metal. Figure 16 shows a sketch of the welding fixture which also holds the welding torch while the work is rotated at the proper speed beneath the arc.

We recapitulate here the steps which are taken in fabricating the glass envelope.

(a) A glass dome the appropriate size is formed by blowing a closed tube of heated glass over a stainless steel mold (IDM Fixture No. 266).

(b) A piece of 1/8" kovar tubing is sealed in the center of the dome.

(c) A flat ring of glass of the required size is formed and joined to the dome.

(d) A brazed kovar ring and tube, which has had the excess copper removed, is outgassed and a glass seal is made to the tubular part. While this glass seal is being made, the kovar ring is held in a special fixture (IDM Fixture 267) to avoid distortion while the kovar is hot.

(e) Using this same fixture, the dome and glass ring are joined to the glass sealed to the kovar ring. This holding fixture is so constructed that it insures that the tube through the glass dome is well centered in the kovar ring and is normal to the plane of this ring. After operation (e) the entire piece is

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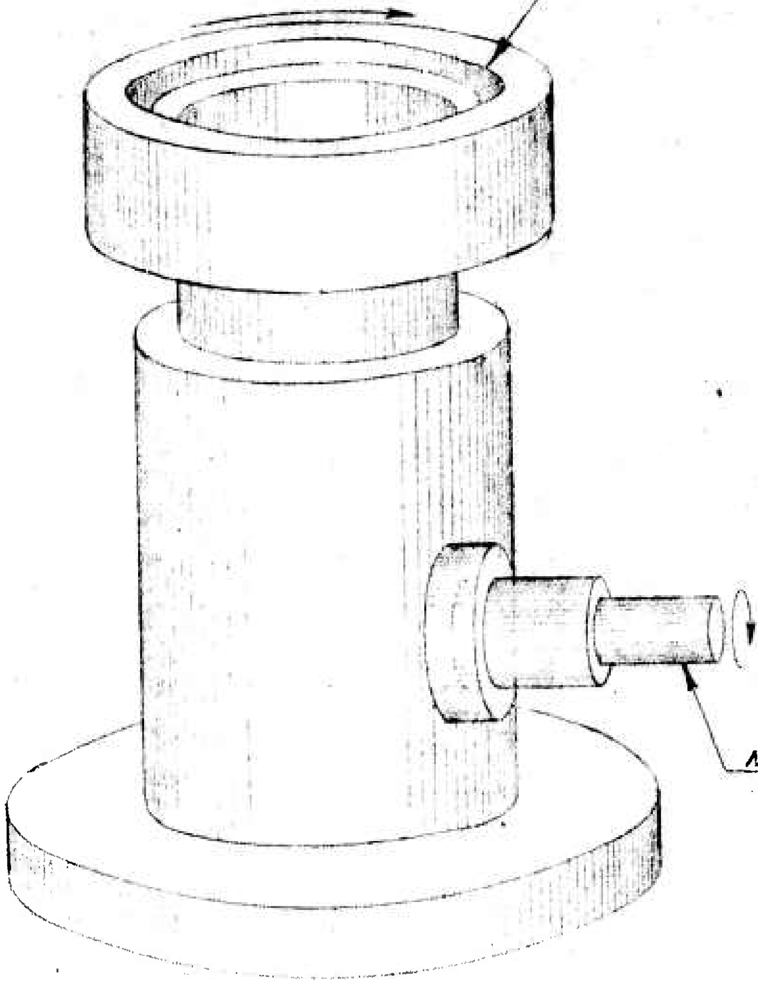

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WELDING FIXTURE FIG. 16

placed in a furnace for strain relief and is cooled very slowly.

(f) After removal from the oven the kovar lead-through wires are sealed into the envelope half, making use of the fixture (IDM Fixture No. 268) built for that purpose. The envelope half is then again placed in the oven for strain relief and cooled slowly.

(g) The envelope half is then waxed into IDM Fixture No. 270; the waxing is done in an oven to make sure that no stresses are set up during the process.

(h) While held in IDM Fixture No. 270, the edges and the top face of the kovar ring are trued up and a groove is cut in the top face in order to provide the proper geometry for the later heliarcing.

(i) Still in this fixture, the interior surfaces of the envelope are ground and polished to dimensions, using IDM Fixture No. 272 for inspection of the surfaces. Following this the envelope half is removed from the holding fixture by dissolving the wax in carbon tetrachloride.

(j) Electrical leads are fastened to the protruding kovar wires by spot welding previously prepared thin copper wires soldered into nickel sleeving, which just fits over the kovar lead-throughs.

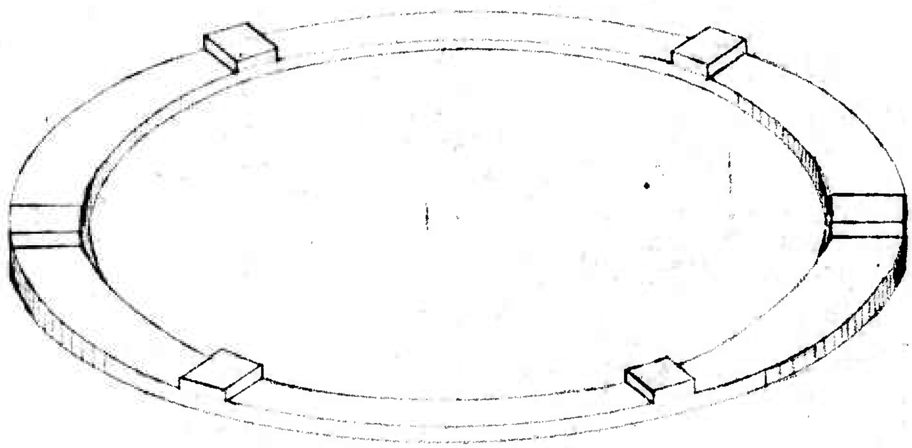
(k) The envelope is then prepared for evaporation of the electrodes by placing it in electrode mask holding fixture together with the mask.

(l) Nichrome electrodes are evaporated upon the interior surface of the envelope half. After evaporation the envelope is reduced to atmospheric pressure in a hydrogen atmosphere and is thereafter only handled in such a fashion as to remain immaculate. When not being handled, it is stored in a dessicating jar.

(m) Meanwhile a kovar tube has been ground and faced off to the proper dimensions; a glass spacer ring, as is shown in Figure 17, and the alignment ring and key, as shown in Figure 18, have been ground and polished.

(n) When two envelope halves have been finished as described, it is planned that a complete assembly, enclosing a rotor, will be placed in welding fixture (IDM Fixture 273) and the entire assembly will be heliarc welded as described earlier in this section.

(o) Following this, it is planned to seal glass tubing to the two ends of the kovar tubing. This will be done by wrapping copper wire around the kovar tubing, approximately one inch from where the seal is to take place, and blowing on this copper while the



GLASS SPACER RING

FIG. 17

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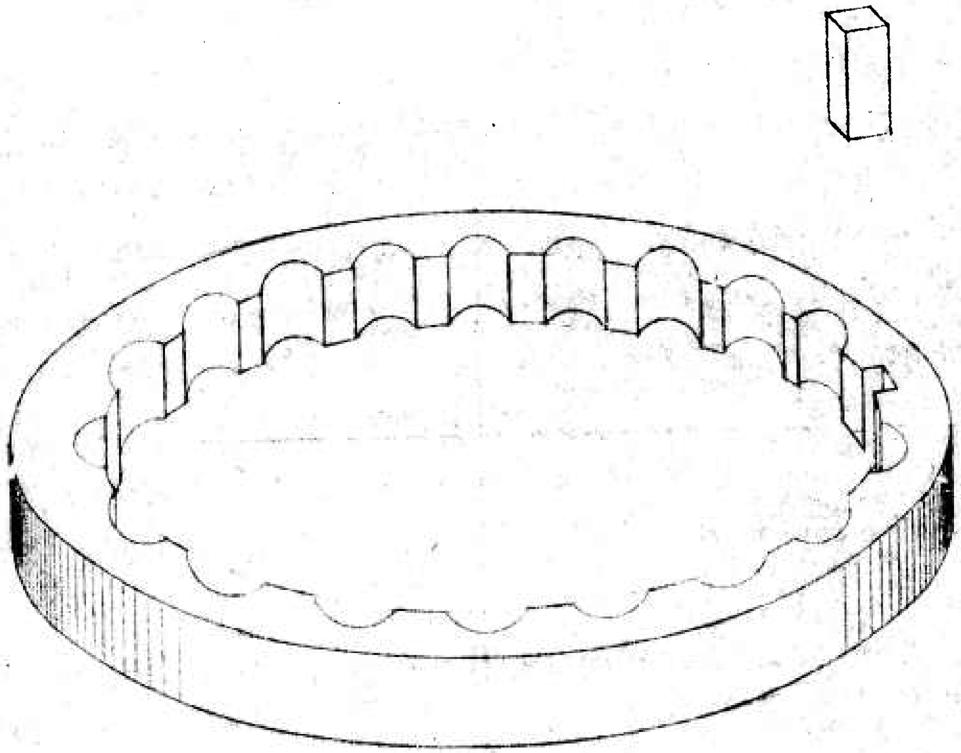

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ALIGNMENT RING & KEY

FIG. 18

seal is being made. This will insure that the kovar on the cool side of the copper will be in no danger of cracking the seal where this tubing joins the envelope. This glass tubing will be used to seal to an ion gauge on one side of the envelope and to an evacuating line and gettering reservoir (see Figure 19) on the other side.

(p) The entire assembly will then be placed in an oven and heated to 250°F for twenty-four hours while attached to a vacuum line. The getter will then be flashed and the assembly will be sealed off as described in an earlier section of this report.

5.0 DESIGN OF ELECTRONICS CIRCUITRY

The details of the electronic circuitry used in connection with the rotor are shown in the attached block diagrams and schematics.

A short discussion of the philosophy of design of these circuits is appropriate.

5.1 SUPPORT SERVO CIRCUITRY

The support servo circuit is the most elaborate circuit designed in connection with this project and it is critical for operation of an electrostatically floated gyro. The principles of servoed electrostatic support are described in Dr. Nordsieck's paper. Our design for

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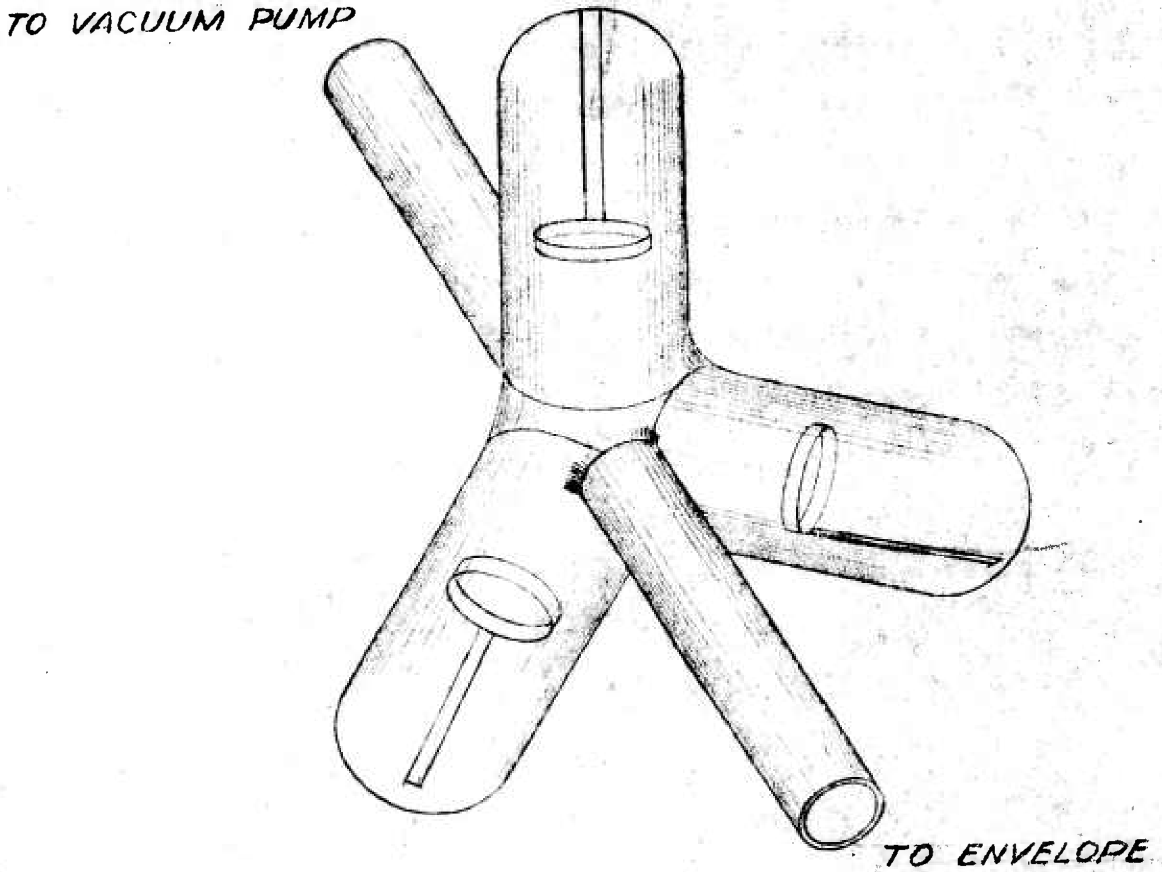

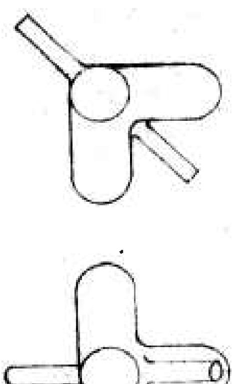

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GETTERING RESERVOIR

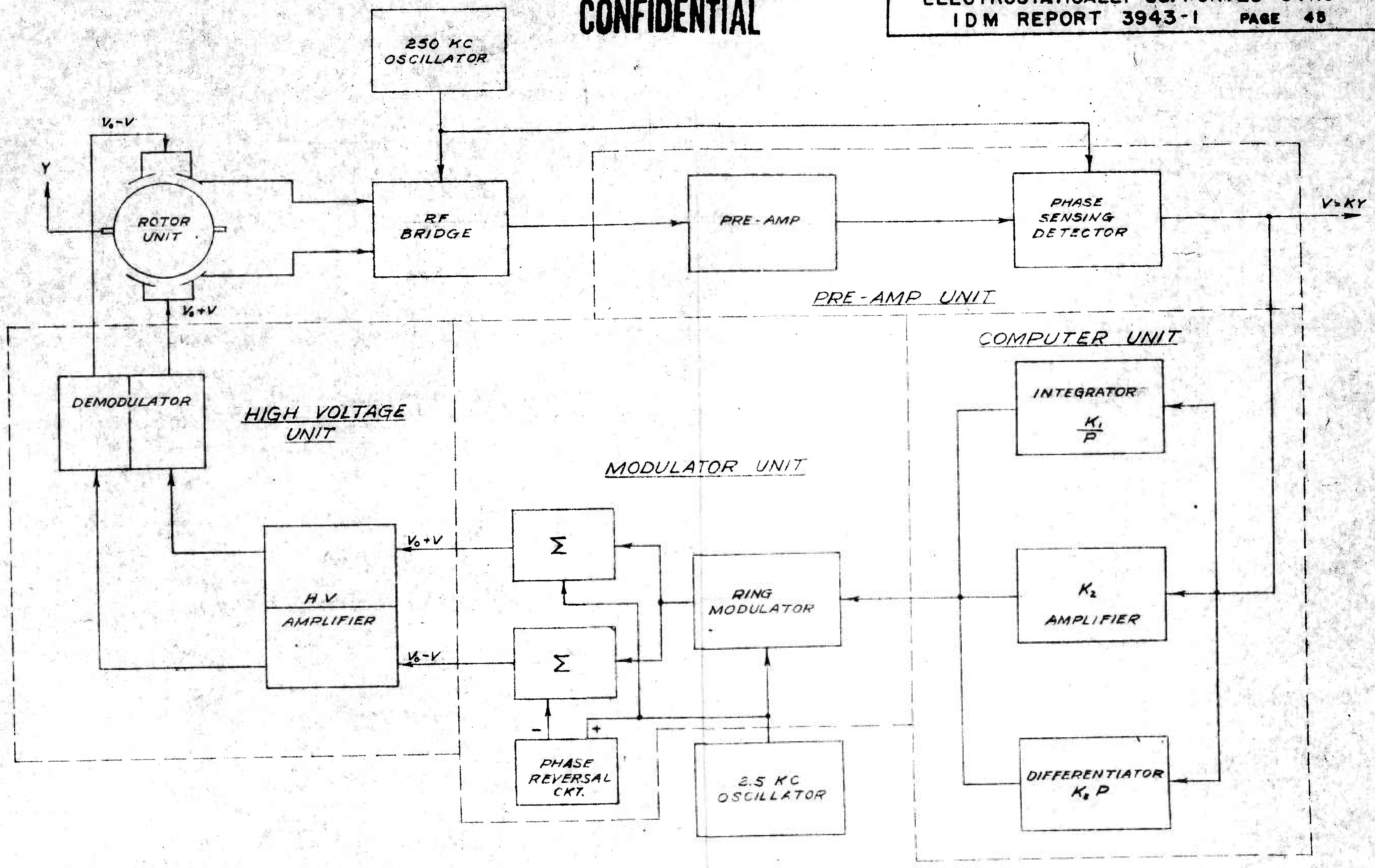
FIG. 19

a circuit to carry out this task is shown in block diagram, Figure No. 20.

The problem is to sense any change in position of the rotor relative to the electrodes by means of a signal from an RF capacitance bridge and to translate this signal back into changes of the supporting voltages in such a way that the negative spring constant inherent in the support system is overcome. This servo circuit is designed so that there are no unstable oscillations and no steady state error. Also, since five support circuits operate simultaneously upon a floated rotor (three spacial supports and two aspect supports), it is necessary to use some method of filtering the signals so that cross talk between the various circuits is negligible.

The two pairs of electrodes associated with any one direction or aspect ofthe rotor are connected as two arms of an RF capacitance bridge fed by an RF oscillator. The bridge is then tuned to a particular frequency so that there is no signal response from different frequencies.

In the circuits for support of the rotor, the driving oscillators differ by 20 kilocycles and operate in the 250 kilocycle range. The sensing voltage on the envelope plates is approximately 5 volts, which does



BLOCK DIAGRAM - SUPPORT SERVO FIGURE 20

not affect the rotor position appreciably.

The signal from the RF bridge, which is in the millivolt range, is fed through a pre-amplifier to a phase sensitive detector where the phase of the signal is compared with the phase of a reference current from the driving oscillator. The output from the phase sensitive detector varies between ± 10 volts DC depending on the amplitude and polarity of the current coming from the RF bridge, which in turn depends upon the position or aspect of the rotor with respect to the electrodes.

The direct current from the phase sensitive detector is fed through the computer unit, which includes a differentiator to damp out oscillations, and an integrating unit to eliminate any steady state error. The straight through gain of the computer unit is approximately .35.

The output from the computer unit is fed to an amplitude modulator which is driven by a 2500 cycle oscillator. This modulator furnishes an alternating potential with an amplitude proportional to the voltage output of the computer unit and which changes phase as the computer output changes sign. This 2500 cycle potential (proportional to a voltage which we call "V") is both added to and subtracted from a reference 2500 cycle potential (proportional to a voltage which we call "V_o")

so that the output of the modulator unit consists of two a.c. potentials, proportional respectively to $(V_o + V)$ and $(V_o - V)$.

These two potentials are fed to identical high voltage amplifiers and then to identical demodulators. The output of the demodulators is thus two d.c. potentials equal to $(V_o + V)$ and $(V_o - V)$. According to our calculations and experiments, the support circuits should operate with $V_o \approx 5000$ volts and $0 \leq V \leq 5000$ volts for the proposed geometry and rotor weight.

It should be remarked that the high voltage amplifiers are center-tapped about a common ground for all circuits. This means that the rotor will be at the common ground potential and cross talk between the various circuits, due to the circuits having a common capacitor plate (the rotor), is reduced to a negligible value.

The reason for having the supporting electrode potentials in the form of $(V_o + V)$ and $(V_o - V)$ is that since the attractive force due to these potentials is proportional to the square of the potential, furnishing these in this form eliminates the squared terms so that the resultant force on the rotor is a linear function of V.

Figures 21 through 25 show the schematics of the circuit described.

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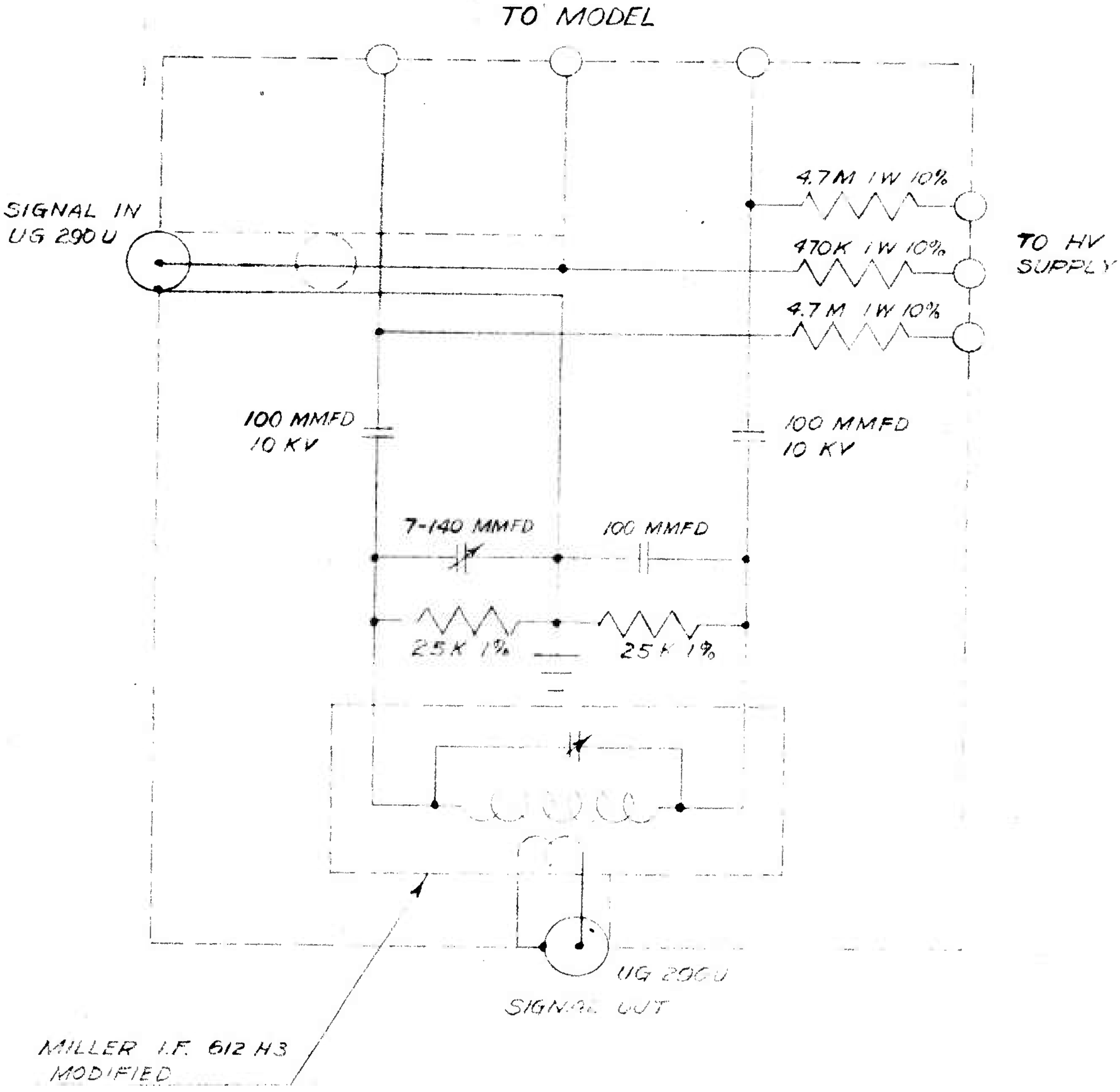

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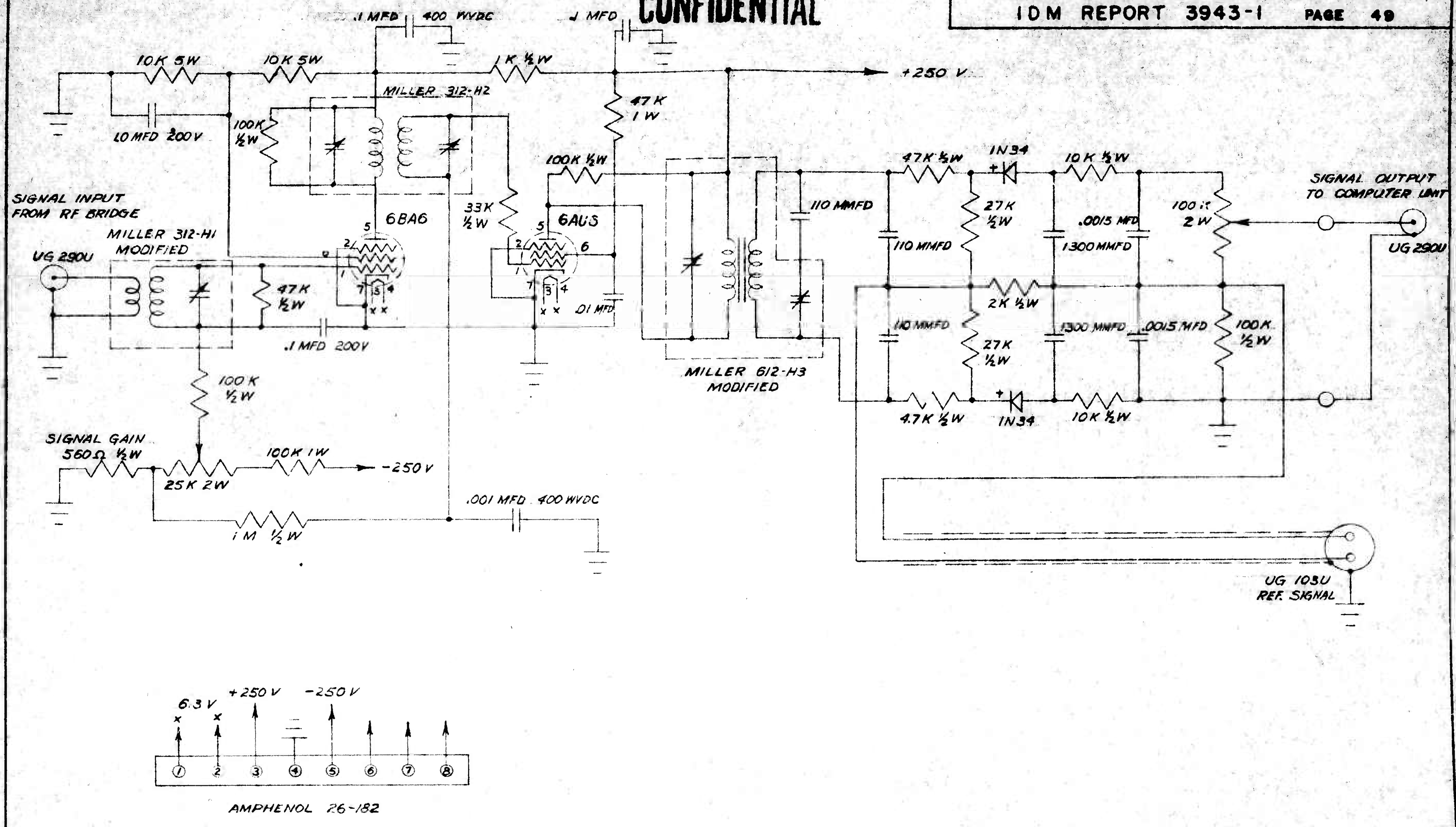
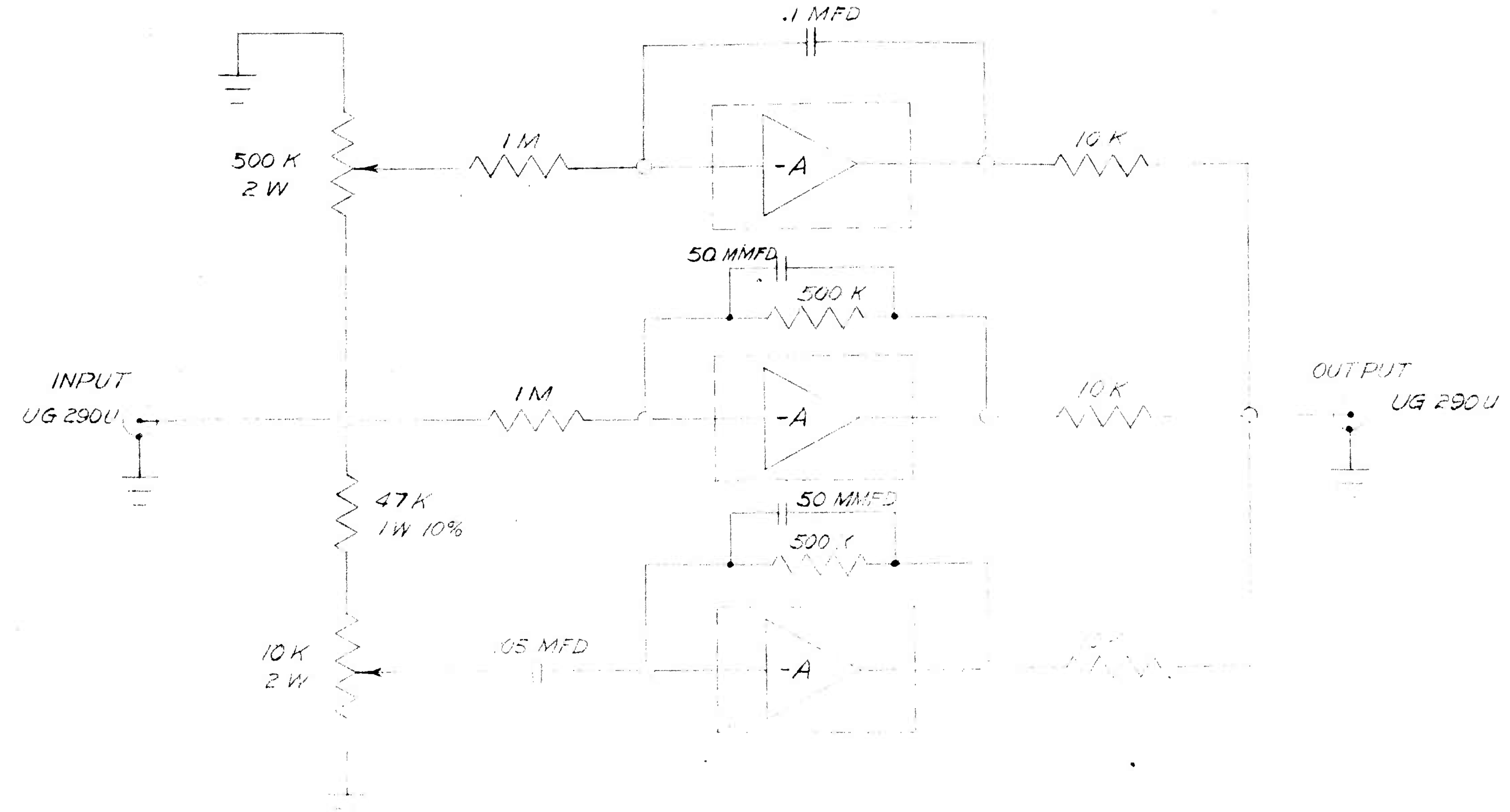
SCHEMATIC RF CAPACITIVE BRIDGE

FIG 21



SCHEMATIC - PRE AMP UNIT - SUPPORT SERVO FIGURE 22



A – BERKELEY MODEL 1048 OPERATIONAL AMPLIFIER

SCHEMATIC - COMPUTER UNIT FIGURE 23

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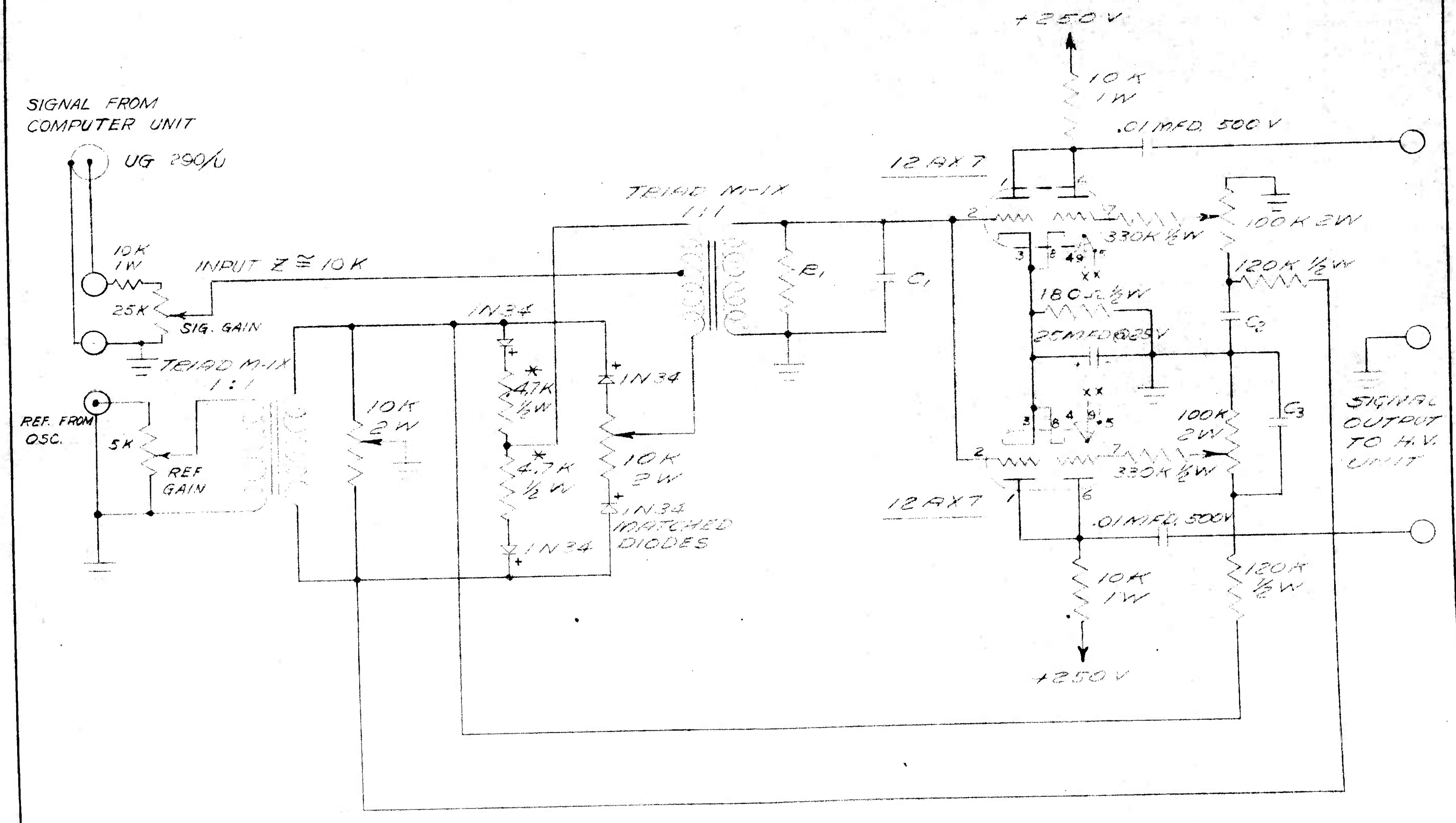

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SCHEMATIC · MODULATOR UNIT FIGURE 24

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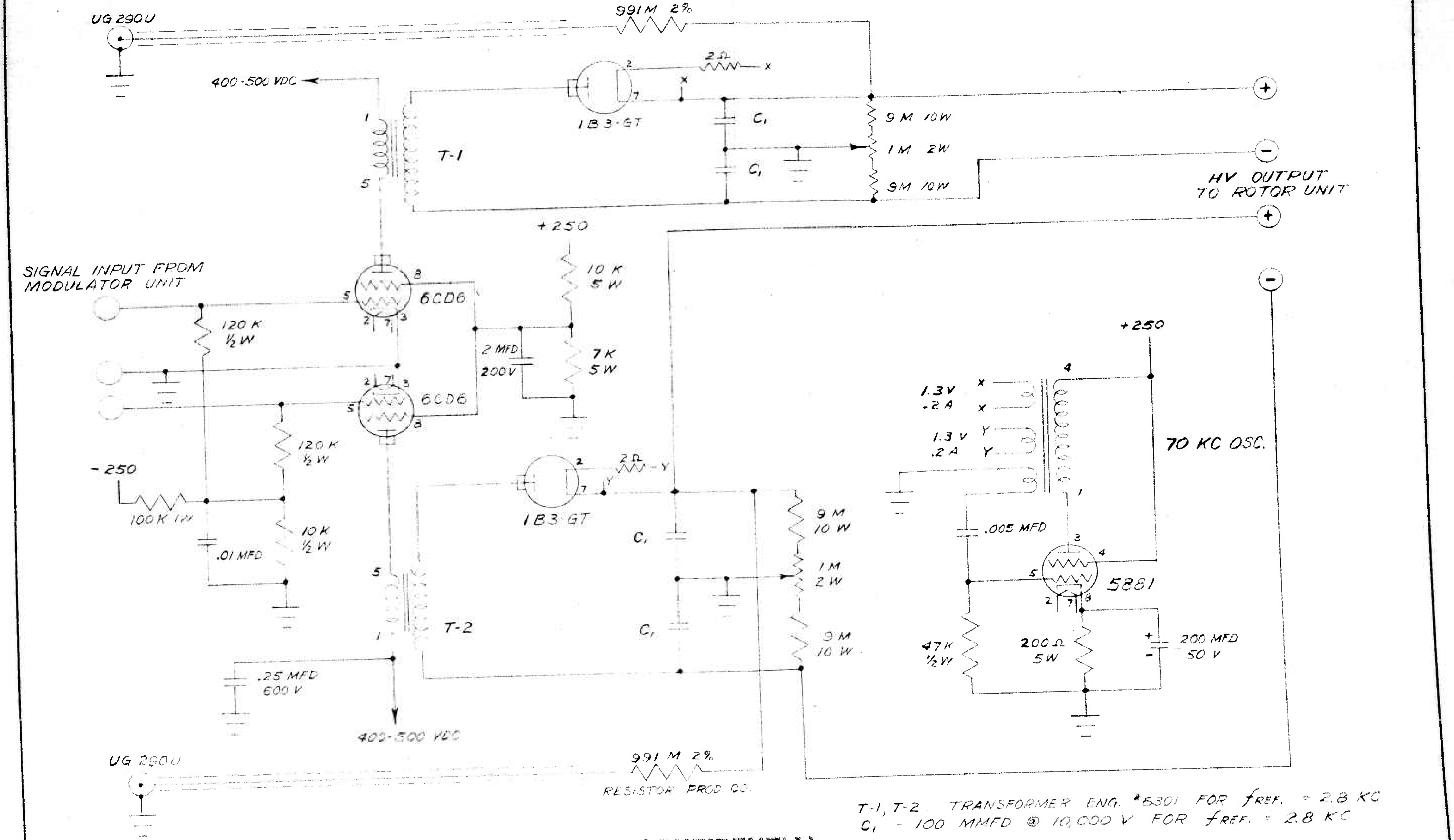

T-1, T-2 TRANSFORMER ENG. #6301 FOR $f_{REF.}$ = 2.8 KC
C_1 - 100 MMFD @ 10,000 V FOR $f_{REF.}$ = 2.8 KC

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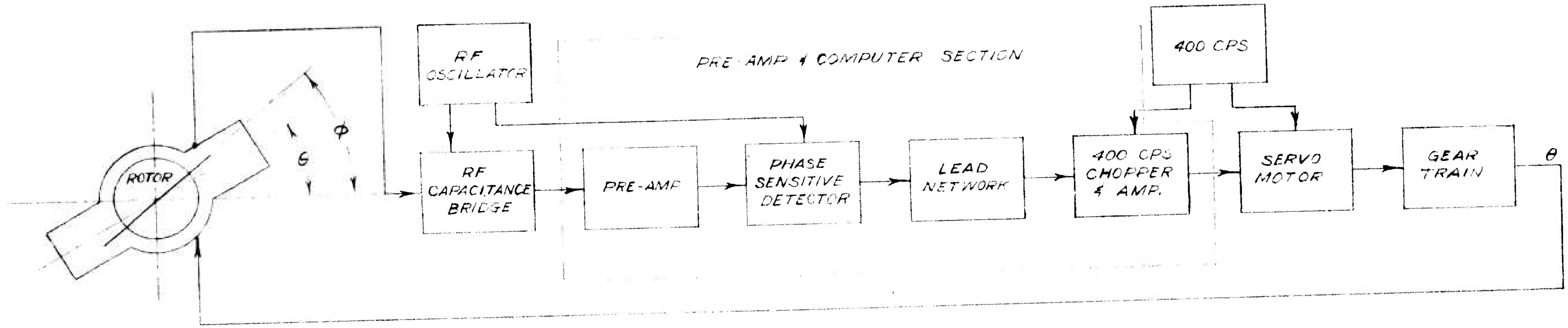
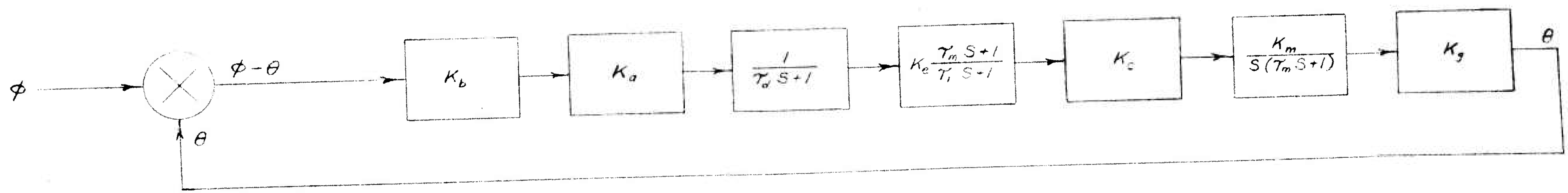
SCHEMATIC - HIGH VOLTAGE UNIT FIGURE 25



(A) FUNCTIONAL BLOCK DIAGRAM



(B) TRANSFER FUNCTION DIAGRAM

BLOCK DIAGRAM - TILT SERVO FIGURE 26

5.2 TILT SERVO CIRCUIT AND DRIVING MECHANISM

The block diagram of the tilt servo and driving mechanism is shown in Figure 26. Here the purpose of the circuitry and attendent mechanism is to physically turn the envelope so that it is lined up with the rotor to a very small angle. For this purpose the electrodes opposite the lateral flange of the rotor are used to furnish two legs of the RF capacitance bridge and the envelope is moved in the appropriate direction by a servo motor through a large gear reduction.

As in the case of the support servo, the signal from the RF capacitance bridge is fed into a pre-amplifier and then into a phase sensitive detector so that the output is a direct current dependent upon the amplitude and polarity of the signal from the capacitance bridge. Because there is no constant force in the tilt servo system corresponding to the gravitational force in the support system servo, there is no need for an integrating circuit to eliminate the steady state error. Thus by the introduction of a lead network, it was unnecessary to build a computer section as was done for the support servo network. The signal from the phase sensitive detector is merely fed through a lead network and then to a 400 cycle per second chopper and amplifier. This

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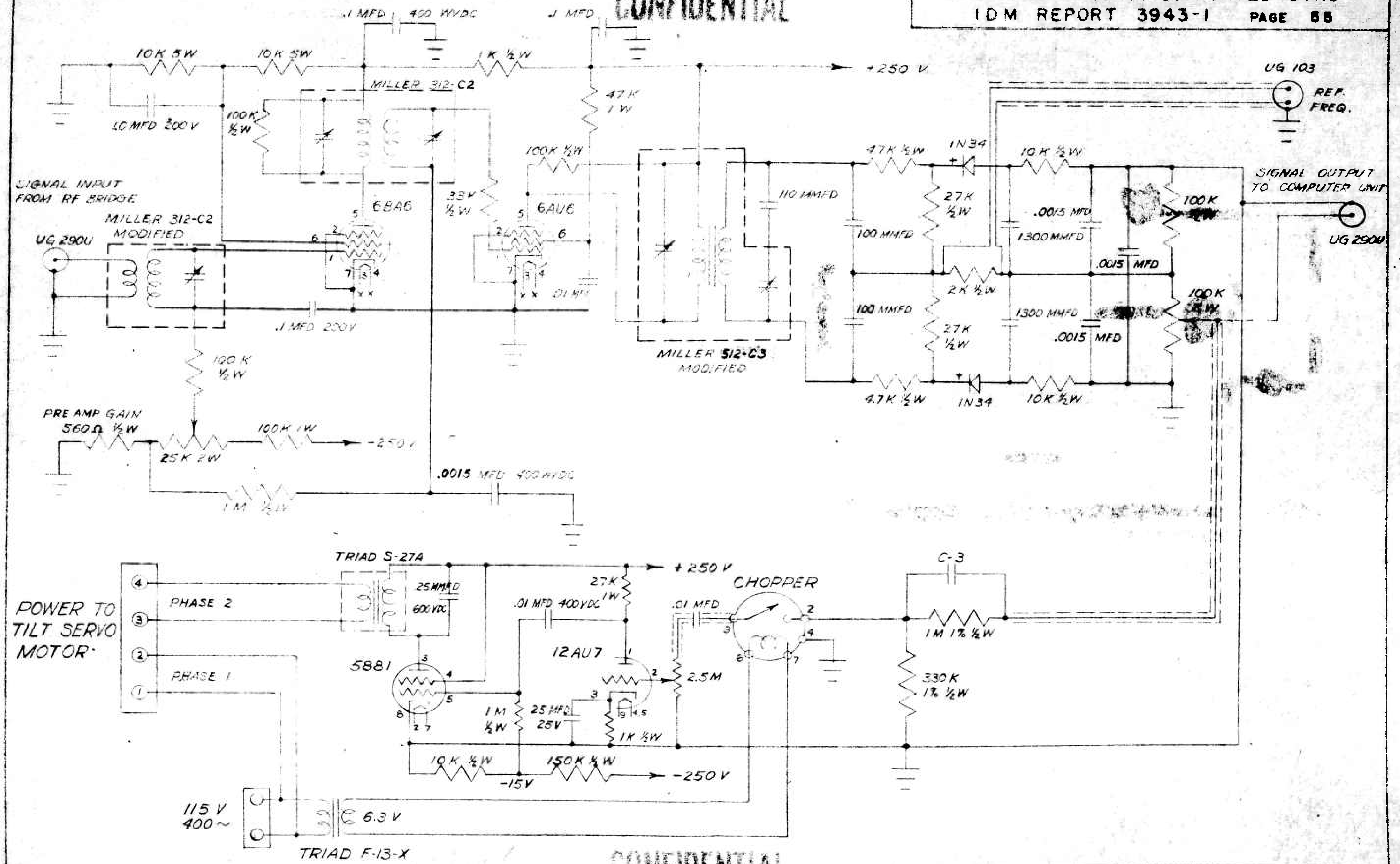

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SCHEMATIC - PRE AMP & COMPUTER, TILT SERVO FIG. 27

amplifier signal is fed to a servo motor which, through high gear reduction, turns the envelope holding the sensing electrodes.

The sensing RF voltage on the flange electrodes is approximately 3 volts, which would not contribute any appreciable extraneous torque.

Figure 27 is a schematic of the preamp and lead network section of the tilt section.

5.3 STARTING COILS

The only other electrical circuitry required in connection with the gyro was that of the starting coils. A schematic of this circuit is shown in Figure 28. This merely provides a rotating magnetic field of approximately 30 gauss rotating at 2,000 cycles per second. This acceleration brings the rotor to 80,000 cycles per minute in approximately 15 to 20 minutes.

Albert S. Cahn

Albert S. Cahn

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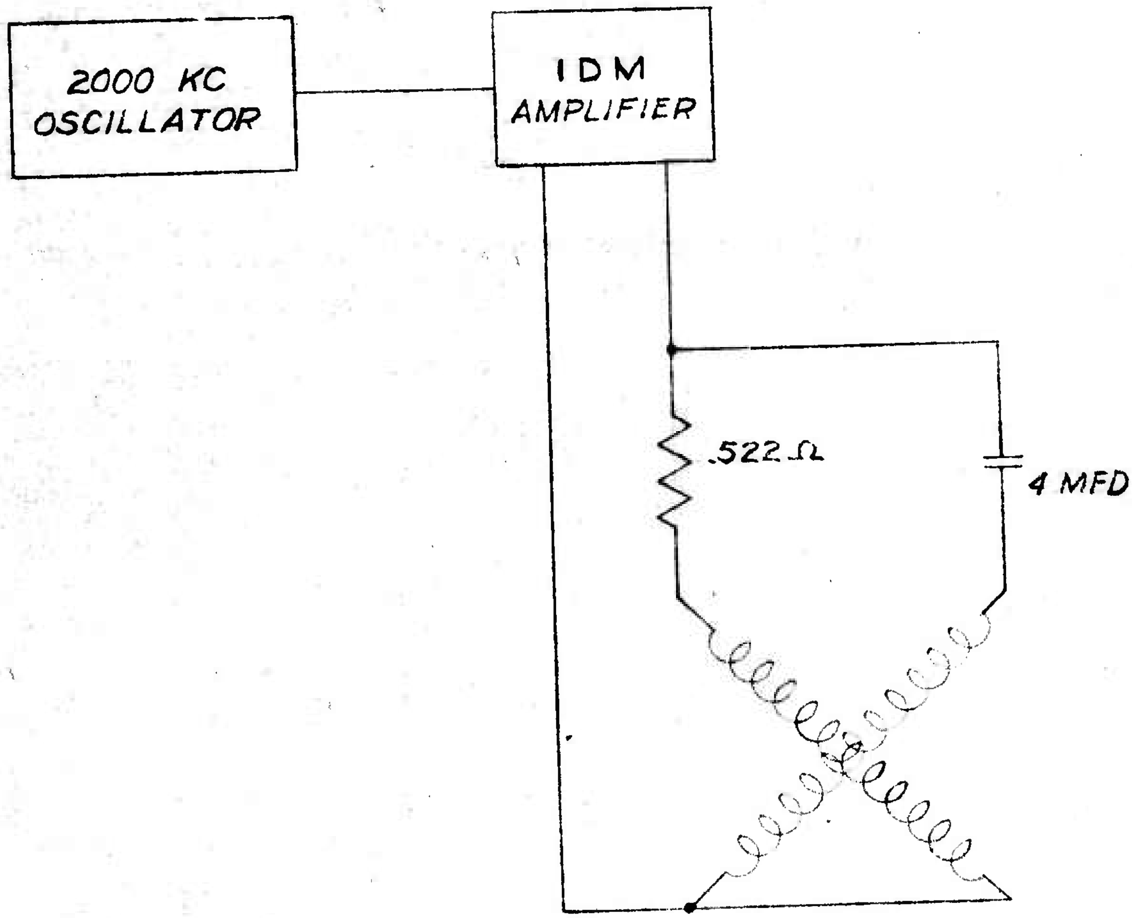

72 TURNS OF #21 LACQUER COATED COPPER WIRE IN EACH COIL.

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SCHEMATIC - STARTING COILS

FIG. 28

Electrostatically Supported Gyro
IDM Report No. 3943-1

APPENDIX

FEASIBILITY OF A FREE GYRO NAVIGATION SYSTEM

by

A. NORDSIECK, UNIVERSTY OF ILLINOIS

May 29, 1954

FEASIBILITY OF A FREE GYRO NAVIGATION SYSTEM

by A. Nordsieck, University of Illinois

1. Introduction

In an earlier paper on this subject, dated 16 March, 1954, of which a copy was sent to Dr. E. Piore of the Office of Naval Research, Washington, D. C., a shperical shell geometry for the gyro rotor, to be floated on electrostatic fields in vacuum, was considered in detail. It was there mentioned parenthetically that a cylindrical geometry also appeared quite favorable. The author has since considered the cylindrical geometry in detail and finds that it has great advantages from the point of view of ease of precise fabrication and from the point of view of easy and accurate detection of the spin axis by electrical rather than optical means. However, the purely cylindrical geometry makes it essentially impossible to insure that the parasitic torques are within the required limits of smallness, barring tolerances of the order of optical tolerances or better. The ease of precise fabrication and of electrical detection are of course highly desirable and would contribute greatly to the probability of success of the scheme; however, the optical tolerances required in the purely cylindrical geometry would be prejudicial to the success of the scheme, especially so in view of the fact that the rotor must spin at speeds of the order of 100,000 r.p.m.

The author has found a compromise geometry, part spherical and part cylindrical, which combines the good features of each of the two pure geometries, and wants in this paper to propose and analyze in detail a design based on this hybrid geometry. The great advantage of the spherical geometry, as explained in the previous (March 16, 1954) paper, is that the electric supporting stresses are guaranteed by the laws of electricity to be normal to the metallic surface and thus give rise to substantially no torque; it is this feature of the spherical geometry that we want to retain.

The rotor geometry now being proposed is briefly as follows: a spherical metal shell with a flat ring projecting from it at and in the plane of the equator (see Fig. 1). The rotor will thus resemble the planet Saturn. The strong supporting forces are to be applied to the spherical part of the surface only, while nothing but exploring fields, giving rise to forces 10^{-6} times the magnitude of the supporting forces are to be applied to the flat surfaces of the ring for purposes of sensing the orientation of the rotor.

In order to avoid referring the reader extensively to the earlier paper, the general introductory discussion is repeated here.

The submarine service has a vital need for a secure means of navigation while submerged; a need which is becoming more acute as the "true submarine," requiring no atmospheric

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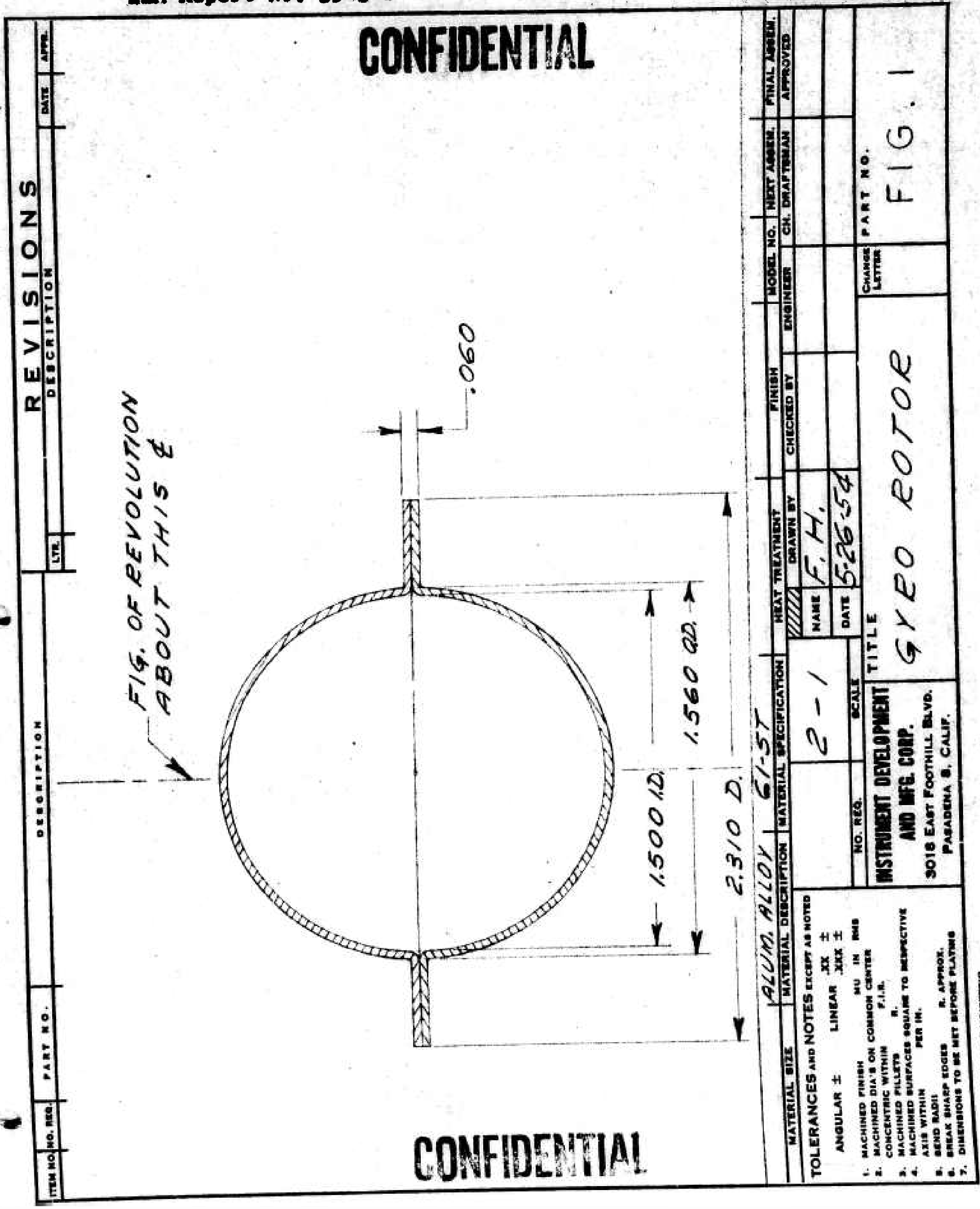

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oxygen for propulsion, becomes a reality. The special features of the submarine navigation problem, as contrasted with guided missile navigation for example, are low speeds, small accelerations, long time periods and an overriding requirement to refrain from radiating any signals. As to navigational accuracy requirements, we may remark that an accuracy of one mile or thereabouts, reckoned per day of elapsed time since a fix, would be very useful.

Knowledge of two or more appropriately chosen fixed directions in space, plus knowledge of the local vertical, plus a chronometer constitute a navigation system, as for example conventional stellar navigation. It has long been realized that in principle the required several fixed directions could be provided by the angular momentum vectors of freely rotating bodies, called "free gyros" to distinguish them from gyro-compasses. However, the requirements of freedom from extraneous torques are so severe that this scheme has been regarded as technically not feasible to date.

In view of the severe Navy need and in view of several modern technical developments it seems appropriate to re-examine the possibility of a free gyro navigation system. The technical developments to which we refer are in particular the ability developed by J. W. Beams and his collaborators(1) to

(1) Beams, Smith and Watkins, Jour. Soc. Mot. Pict. Televis. Engrs. 58, 159, Feb., 1952

Beams, Ross and Dillan, Rev.Sci.Instrum., 22, 77, Feb., 1951

support rapidly spinning objects by electromagnetic fields alone in vacuum and the modern art of electronic servo-machinery.(2)

In this paper a design for a free gyro is described (Section 2) and the parasitic torques due to all known causes are estimated (Section 3). It is concluded that a drift of the spin axis of less than one minute of arc per day, corresponding to one mile on the surface of the earth, can be achieved with some engineering margin. Section 4 contains some suggestions on methods of fabricating the rotor. Section 5 discusses the methods proposed for sensing the spin axis of the rotor. Section 6 contains a brief discussion of the problems connected with bringing the rotor up to speed. Finally, Section 7 contains a proposal for an initial development which is more modest than a full-fledged navigation apparatus, but which will nevertheless answer the question of the feasibility of a free gyro system and will determine the accuracy attainable in practice with such a system.

No discussion is devoted in this paper to the problem of determining the local vertical because it is felt that the vertical problem is relatively straightforward and easy compared to the free gyro problem, especially on a platform as stable as a submerged submarine and when averaging times

(2) See for example M.I.T.Radiation Laboratory Series, Vol. 21, "Electronic Instruments," McGraw-Hill, 1948, and Vol. 25, "Theory of Servo-mechanisms," McGraw-Hill, 1947

of several minutes are permissible. The error in a position reading due to error in the local vertical is of course not cumulative in a free gyro system, in contrast to inertial systems. That is, if at one time the local vertical is poorly determined and at a later time better determined, the position at the later time will have an accuracy limited by the accuracy of the vertical at that time only. A detailed analysis of appropriate vertical-determining methods will be presented in another paper.

The chronometer is not a problem.

The free gyro system could be made automatically and continuously to display absolute latitude and longitude on dials, and in addition, average course and speed relative to the earth, averaged over several minutes. It is believed that this continuously available information would greatly improve the efficiency of submarine operations.

2. Description of Free Gyro

A high degree of symmetry is essential in reducing the parasitic torques tending to turn the axis of the gyro to tolerable levels, as will become evident from the torque estimates of Section 3. For this reason the author first considered a spherical geometry for the rotor. As explained in the introduction, we now want to consider a hybrid spherical-cylindrical geometry.

The choice of weight and size of the rotor are

influenced by the consideration of whether to support the rotor by magnetic fields or by electric fields. Now the magnetic method, while it has been used more and can support very heavy weights in practice, involves using ferromagnetic material in the rotor, and this is immediately and completely ruled out by the magnitudes of the parasitic torques due to stray magnetic fields. Consequently, the support must be by electric fields and this in turn means that the rotor should be light weight so that the supporting voltages are not excessive. A light, strong, non-ferromagnetic material such as Duraluminum is indicated.

The consideration of the most efficient storage of angular momentum also influences the choice of rotor size and weight. For a given mass of material of given strength, one can store the most angular momentum by distributing the mass on the average as far from the axis of rotation as possible. There is a practical limit, however, to the process of moving the material farther from the axis; since for a given total amount of material, the sections will eventually become too thin for precise fabrication and for dimensional stability. If, on the other hand, the section is kept constant and the rotor is otherwise scaled up in size, no advantage is gained because the angular momentum stored and the parasitic torques vary exactly proportionately. For these reasons we shall

consider a rotor of quite small size and weight: The spherical part is to be 1.5 inches in diameter and the total weight of the rotor is to be 1/2 ounce. We do not imply that another size and weight, say half or twice as heavy, would be a poor choice, but we want to consider definite dimensions and weight for the sake of concreteness of the discussion.

A sketch of the proposed rotor is given in Figure 1. The maximum reasonable rotation speed is determined by the requirement of keeping safely within the yield point of the material, and we propose 80,000 r.p.m., which stresses the material to one-third of its yield point. Further pertinent data are:

rotor mass	15 gm.
maximum stress	7×10^8 c.g.s. = 10,000 p.s.i.
maximum strain	10^{-3}
angular speed	1,333 r.p.s. = 80,000 r.p.m.
moment of inertia	58 gm-cm^2
angular momentum	4.9×10^5 c.g.s.
supporting field	70,000 volts/cm.
supporting potential	5,200 volts

The centrifugal stress is quite conservative and will cause an elastic centrifugal distortion of the spherical part of the rotor of less than 0.001 inch. The supporting electric field figure is based on using 80% of the spherical surface area for support, and the supporting potential figure is based on a clearance gap of about 1/64 inch between the surface of the rotor and the adjacent stationary electrodes.

A brief explanation of the principle of supporting a

metallic object by electric fields without mechanical contact is probably in order here. According to the laws of electricity any pair of condenser plates between which a potential gradient or electric field exists, are attracted toward one another with a force, $E^2/8\pi$ dynes per square centimeter of plate area, where E is the potential gradient or electric field in statvolts per centimeter (one statvolt equals 300 volts). In order to avoid having to make contact with the rotor, we placed two stationary plates or electrodes opposite two different areas of the rotor surface, thus forming two condensers in series, and make connections to the two stationary electrodes only. Since we must stabilize and support the rotor in all three dimensions, we need to supply such electric forces along three mutually perpendicular axes, and for each of these three axes, because we can only supply attraction and not repulsion by this means, we must provide two pairs of condensers diametrically opposite one another. Thus a total of six condenser pairs is required to support the rotor and stabilize its position in three dimensions for any arbitrary orientation. The proposed arrangement and disposition of the corresponding twelve stationary electrodes is illustrated in Figure 2. In order to avoid electrical interaction between different condenser pairs, the potential difference supplied to each electrode pair must be center-grounded to a common ground point. The rotor will then assume a potential equal to the potential of

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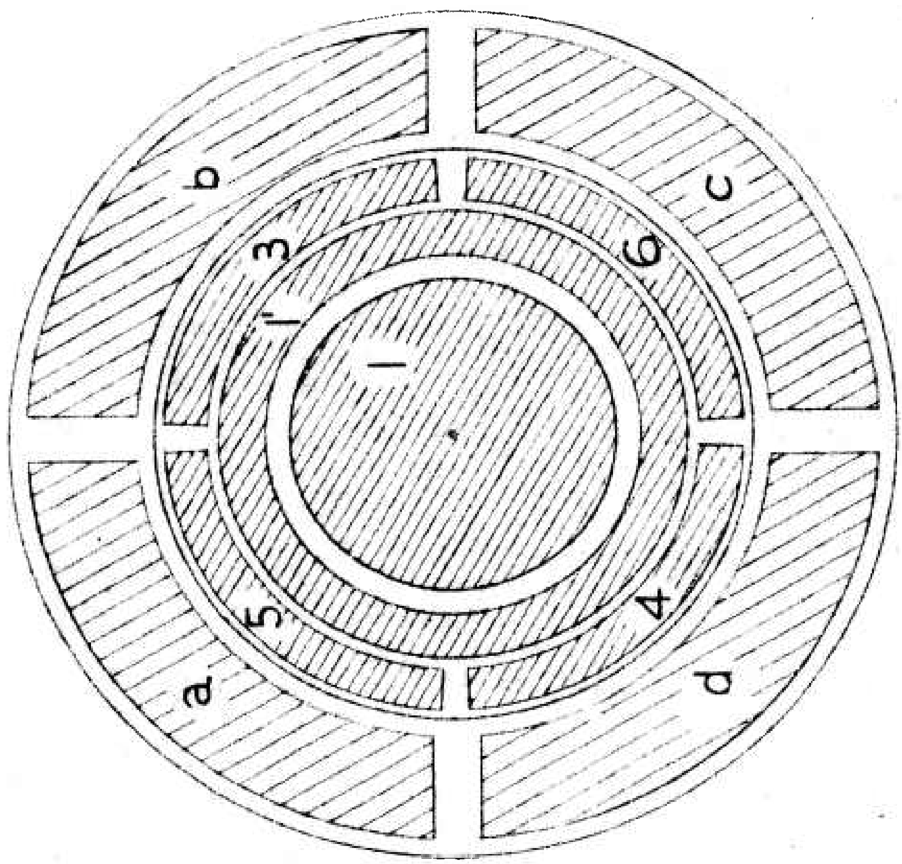

REVISIONS

LTR.	DESCRIPTION	DATE	APPR.

ITEM NO.	NO. REQ.	PART NO.	DESCRIPTION

TOLERANCES AND NOTES EXCEPT AS NOTED

ANGULAR ± LINEAR .XX ± .XXX ±

1. MACHINED FINISH MU IN RMS
2. MACHINED DIA'S ON COMMON CENTER CONCENTRIC WITHIN F.I.R.
3. MACHINED FILLETS R.
4. MACHINED SURFACES SQUARE TO RESPECTIVE AXIS WITHIN PER IN.
5. BEND RADII
6. BREAK SHARP EDGES R. APPROX.
7. DIMENSIONS TO BE MET BEFORE PLATING

MATERIAL SIZE | MATERIAL DESCRIPTION | MATERIAL SPECIFICATION | HEAT TREATMENT | FINISH | MODEL | NEXT ASSEM. | FINAL ASSEM.

NO. REQ. | SCALE

	DRAWN BY	CHECKED BY	ENGINEER	CH. DRAFTSMAN	APPROVED
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DATE	5-26-54				

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TITLE SUPPORTING STRUCTURE EQUATORIAL SECTION SHOWING ELECTRODES

CHANGE LETTER

PART NO. FIG. 2

CONFIDENTIAL

this common ground point. The magnitudes of the potentials applied to the various electrode pairs are determined by three electronic servo circuits which sense the difference in capacitance of diametrically opposite condenser pairs by high frequency AC bridge methods and always act to alter the supporting potentials in such a sense that the rotor is restored to the center of the supporting structure, i.e. the bridges are balanced. The large supporting potentials may be either DC or some moderate audio frequency AC such as 400 cycles per second, depending on which is preferable from the circuit design point of view; the frequencies at which the AC bridges are operated are probably conveniently chosen in the one megacycle range.

The space between the spinning rotor and the supporting electrode structure must be evacuated for two reasons: to avoid electric breakdown from the high potential gradients, and to reduce the gaseous drag on the spinning rotor. A degree of vacuum such as that employed in the electron tubes is adequate for both these purposes.

The supporting electrode structure and vacuum envelope is to be of the form of an insulating rigid envelope - glass seems the appropriate material - whose inner surface conforms to the exterior surface of the rotor except for a clearance gap of the order of 0.015 in. all round. In Figure 2 we give

a sectional view of half the supporting structure, the section being taken in the equatorial plane. The electrodes are to be affixed to the interior surface in the pattern shown, with electrical terminals brought out from them. The electrodes labelled 1, 1', 3, 4, 5, 6 are arranged on the hemispherical concave part of the interior surface, and together with their "opposite numbers," 2, 2', 3', 4', 5', 6' on the other half of the concave spherical surface, constitute the six pairs of supporting electrodes to which the large supporting potentials are applied. 1 and 1' are partners of a pair; 2 and 2' are partners; 3 and 3' are partners, etc. Note that all the strong supporting fields act upon the spherical part of the rotor surface, which is advantageous from the point of view of minimizing the parasitic torques, as remarked in the introduction. Electrodes a, b, c, d are affixed to the flat portion of the supporting envelope opposite the flat sides of the ring portion of the rotor. These electrodes have an entirely different purpose from the electrodes 1, 1', 2, 2', etc.: they are to carry high frequency potentials of small magnitude (of the order of one volt) and are connected into two further bridge and servo circuits which sense the orientation of the rotor, as distinguished from its position, and control motors which keep the supporting envelope aligned with the rotor.

An important feature of the electrode pattern is that it has an axis of symmetry coinciding with the axis of symmetry

of the supporting envelope structure. Since the envelope structure is to be automatically kept lined up with the rotor, the axis of symmetry of the electrode pattern will coincide with that of the rotor within very small angular limits.

The principle of keeping the supporting structure lined up with the rotor spin axis is essential for reducing the torques sufficiently. The alignment must be held to within one minute of arc or better since the fixed direction in space is not read directly from the orientation of the rotor, but from the orientation of the supporting envelope, and this fixed direction must be read to within one minute of arc. How accurately can we expect to keep this alignment? The A.C. bridges which measure the orientation of the rotor relative to the envelope (operating off electrodes a, a'; b, b', etc.) can readily be balanced to one part in 10^4 by conventional circuit techniques. This means that the circuits will respond to a tipping of the rotor ring by $10^{-4} \times 0.015$ inches at its edge, and since the radius of the ring is about one inch, the detectable angle is 1.5×10^{-6} radians = 1/200 minute of arc. This accuracy is better than necessary for the purpose of indicating the angle correctly, but the magnitude of the parasitic torque also depends on the accuracy of alignment. We shall therefore assume that the misalignment, called δ hereafter, is in actual operation kept within 0.1 minute of arc or 3×10^{-5} radians. The value of δ will figure importantly

in the torque estimates of the following section.

The proposed method of putting the gyro into operation is as follows: The rotor is first floated by means of the servo-controlled electric fields, before it is rotated. Then by means of coils around and attached to the supporting envelope, a rotating magnetic field is applied to the rotor, as in an induction motor. As soon as the torque due to this rotating magnetic field has brought the rotor up to operating speed, the rotating field is turned off completely and the rotor coasts freely thereafter. In normal operation the angular momentum lost in the course of time, due to retarding torques, will be replaced by turning the rotating field on again for a short time; but this must be done only when a navigational fix is available. In order to shut the gyro system down entirely, one must first turn the rotating field on in the reverse sense in order to bring the rotor to rest, before turning off the supporting circuits.

One last point merits discussion in this section, namely the question of how much mechanical vibration and shock the system of electric floating of the rotor can tolerate. We first remark that the electric floating scheme, which was found preferable to the magnetic scheme for other reasons, is definitely superior to the magnetic scheme in respect to resistance to shock and vibration also. This is because the servo loops have to control only the electrostatic energy in

the capacitors, which is much less energy than the magnetic energy stored in a corresponding supporting electromagnet. Hence, the electric system has inherently less inertia and a shorter response time. A response time of the order of milli-seconds is perfectly feasible, so that vibrations of frequencies up to about 500 cycles per second would be followed by the system. The amplitude of vibration which the system could follow is determined by the maximum potential available for application to the electrodes. If this maximum potential is made twice the normal supporting potential, then since the supporting force varies as the square of the applied potential, the system will handle accelerations of 4g horizontally, 3g upward and 5g downward. Vibrations of frequencies greater than 500 cycles per second will not be followed by the system, but the rotor displacements due to such high frequency vibrations are negligible unless the amplitude exceeds 10g. We conclude that the electric floating system can be made to have very high tolerance of vibration and shock even without pushing the art to its limits.

3. Estimate of Parasitic Torques

We shall discuss all of these torques in terms of their two components, parallel, respectively normal, to the spin axis. The parallel components will slow the rotor down and should therefore not exceed about

$$\frac{4.9 \times 10^5}{0.87 \times 10^6} = 0.6 \text{ dyne-cm}$$

in order that the rotor keep spinning (coasting) for about 10 days. We shall see that the parallel component torques can readily be kept an order of magnitude smaller than this. The normal components of torque will cause drift of the spin axis and should therefore not exceed about

$$\frac{4.9 \times 10^5}{.87 \times 10^5 \times 57 \times 60} = 1.6 \times 10^{-3} \text{ dyne-cm}$$

in order that the spin axis drift not more than one minute of arc in a day. This is, of course, a very small torque and is the reason why such elaborate precautions must be taken in the design. Our estimates indicate that we can in fact keep within this limit, with an order of magnitude leeway. In other words, it appears from our theoretical analysis that a drift of one minute of arc per day is definitely achievable, while one-tenth minute of arc per day may possibly be attained.

There are just three known causes of torque on the rotor: gas in the space between the rotor and the supporting envelope, electric forces and magnetic forces. Gravity causes no torque because the forces of gravity are equivalent to a force acting upon the center of mass of the rotor, and since the rotor is not constrained by any mechanical bearings or the like, it chooses its own axis of rotation, which axis passes through the center of mass according to the laws of mechanics.

We discuss the torques due to the three above listed causes in order. Consider first the torque due to the gas surrounding the rotor. (Gas inside the rotor will turn with the rotor and cause no torque.) If the gap is uniform over the whole rotor surface, this torque has a parallel component only. A simple viscosity calculation shows that air at atmospheric pressure in the gap would cause a retarding (parallel component) torque of the order of 15,000 dyne-cm and would therefore slow the rotor down appreciably in a time of the order of one minute. This fact, plus the consideration of electric breakdown, dictates that the space must be evacuated.

For a vacuum of 10^{-6} mm of mercury, we have "Knudsen conditions," i.e. the mean free path of a molecule is much greater than the gap. Under these conditions the retarding torque has to be estimated by considering the transport of tangential momentum by the gas molecules between the moving rotor surface and the stationary envelope surface as the molecules bounce back and forth between these two surfaces. The number of molecules per cc at the above pressure is 3.5×10^{10}. If a typical molecule is nitrogen, its mean speed is 3×10^4 cm/sec. The tangential momentum transferred by one molecule in a round trip between the two walls is 9×10^{-19} c.g.s. Thus the tangential stress is

$$1/2 \times 3 \times 10^4 \times 3.5 \times 10^{10} \times 9 \times 10^{-19} = 4.7 \times 10^{-4} \text{ dynes/cm}^2$$

The effective area is about 60 cm^2 and the effective lever arm about 2 cm, hence the retarding torque comes to

$$4.7 \times 10^{-4} \times 2 \times 60 = 0.06 \text{ dyne-cm}$$

This torque would permit the rotor to coast for about 100 days. Dr. Beams' experience (see references, Page 4) gives practical confirmation of these estimates. He observes a deceleration of the order of 0.1 r.p.s. per hour, on a considerably heavier rotor, and attributes this deceleration to residual gas viscosity. Our theoretical estimate is conservative in one point: we assume that 100% of the tangential momentum is transferred at every round trip; the actual percentage is probably closer to 50%.

As to the more critical normal component of torque, there may be some of this component due to the gas if the gap is non-uniform around the rotor in an unfavorable way. However, the stress on the rotor surface due to gas viscosity is tangential to the surface, so that to the extent that the rotor is a figure of revolution about its axis, the normal component of torque will again be nominally zero. We may be confident then that the actual normal component of torque is less than 1/100 of the parallel component, i.e. less than 6×10^{-5} dyne-cm, which is well within the permissible value of the normal component.

Summarizing the discussion of torques due to gas, we may say that provided a good vacuum is maintained, these

torques can be made 1/10 to 1/100 times the required limits of smallness.

We consider next the torques due to the supporting electric fields. If the spherical portion of the rotor surface were a geometrically perfect spherical surface, then because of the rule that electric lines of force enter a conducting surface normally, there would be no torque whatsoever.

It is true that the metal surface has a finite resistivity and that the induced charges must move relative to the metal, so that there are currents flowing in the metal and there is a consequent ohmic dissipation of energy and an associated retarding torque. However, a simple calculation shows that the retarding torque due to this effect is of the order of 10^{-9} dyne-cm, or entirely negligible. This is the only contribution of the electric fields to the parallel components of torque.

The normal component electric torques with which we are concerned are then associated with departure of the rotor surface from sphericity. Now if the rotor is accurately made, the major cause of departure from sphericity, in the nominally spherical part of the rotor surface, is distortion due to centrifugal stress. (One may even fabricate the shell so that it is slightly prolate when not rotating and becomes more nearly spherical when rotating. The centrifugal distortion

car be readily estimated and allowed for in the fabrication. In our discussion this possibility is not appealed to and this is a point in which our estimates are conservative.)

We next remark that the centrifugal distortion produces a figure which is still a figure of revolution about the axis of the rotor. If then the supporting fields form a pattern symmetrical about an axis, and if this axis coincides with the rotor axis, then even in the presence of distortion of the spherical surface there is no torque. In other words, the normal component of torque involves the product of two small quantities, the angle between the local normal to the rotor surface and the radius (which is a measure of the departure from sphericity) and the angle between the rotor axis and the axis of the supporting structure (above called δ). The first factor is of the order of the centrifugal stress, i.e. 0.001. On this basis we find that in the worst case (i.e. worst attitude relative to the vertical and poorest possible location of the supporting electrodes relative to the centrifugal distortion pattern of the rotor) the normal component of torque can amount to

$$15 \times 980 \times 0.002 \times 3 \times 10^{-5} = 0.9 \times 10^{-3} \text{ dyne-cm}$$

which is just within the allowable limit. The factors in the above product have the following significance: 15 x 980 is the supporting force in dynes; 0.002 is the lever arm in cm

and is compounded of an angle 0.001 radian between the local normal and the radius, and a radius of 2 cm; 3×10^{-5} is the assumed value of δ in radians.

Some additional explanation is probably in order here as to why the factor 3×10^{-5} appears in the above calculation. Assume that the rotor axis is oriented at some intermediate angle with the vertical, such as 45°. The supporting force must then, of course, be directed at 45° to the rotor axis. Now instead of producing this effect by applying a single force at the required angle, we produce the same resultant force by applying two forces, one directed along the rotor axis (from electrodes 1, 1' or 2, 2' of Figure 2) and one normal to the rotor axis (from electrodes 3, 3' etc.). If a single force were applied at the required angle, the torque calculation would not involve the factor $\delta = 3 \times 10^{-5}$ and the torque would be intolerably large. Each of the two forces applied symmetrically with respect to the rotor has a torque proportional to δ because if there perfect alignment the torque would vanish by reason of symmetry. Stated in other terms, we apply forces to the rotor which are always either parallel to its axis within an angular error δ or normal to the axis within the same amount. This is one instance of the high degree of symmetry so often mentioned as necessary to the success of the scheme.

The calculation of normal component of electric torque which we have made is conservative in another respect. The

misalignment angle δ can have either sign, and for a well designed servo system will be as often positive as negative. On account of this the normal component of torque will tend to be random instead of systematic as we have assumed. For a perfectly designed servo system with a time constant of one second, we should multiply the above torque estimate by $(1/.87 \times 10^{-5})^{1/2} = 0.0034$. Evidently a moderately good design of the servo loop will yield an average torque as small as 1/10 the required limit of smallness.

Torques due to a combination of the electric supporting fields and fabrication irregularities of the nominally spherical surface are more difficult to discuss. As an example for orientation, let us assume a bump in the surface of 1/4" in diameter and 0.01 mil high at its center. Such a bump will cause an average torque only if it passes partly under an electrode with a considerable potential on it. Assuming the worst case, namely that half the bump passes under an electrode exerting its maximum force, we find an average normal component of torque of 1×10^{-2} dyne-cm, or about 6 times the permissible value. Now such a bump is not a normal type of irregularity in a machined part which is a figure of revolution. Clearly good, but not impossible precision of fabrication of the rotor is called for.

Besides the large supporting electric forces there are relatively small electric forces due to the high frequency

electric fields incidental to the A.C. bridge functions. The potentials involved will be of the order of one volt as compared to 5000 volts for the supporting fields, consequently the forces will be $1/(5000)^2$ as large. Furthermore these high frequency fields are more symmetrically distributed than the supporting fields. All the high frequency fields applied to the spherical portion of the rotor will therefore produce entirely negligible torques. The high frequency fields applied to the flat portions of the ring, if they are out of balance between top and bottom of the ring by 1%, will produce a normal component of torque estimated at 6×10^{-8} dyne-cm, or also entirely negligible.

Summarizing the estimates of torques due to electric fields, we may say that the estimates indicate a high degree of probability that the requirements can be met and a definite possibility of achieving 1/10 minute of arc per day.

Consider finally the torques due to magnetic fields. (There is no combination electric-magnetic effect because there are no average currents in space due to the electric supporting fields.) We shall assume that the stray steady magnetic field acting on the rotor is 1 gauss maximum, which requires no shielding. The stray magnetic field will have three effects: It will produce a torque if there is any permanent (ferromagnetic) moment in the rotor; it will produce a retarding torque by inducing currents in the rotor and it will

produce a paramagnetic moment in the rotor.

Ferromagnetic material cannot be tolerated in the rotor because the ferromagnetic moment would then be of the order of 10 electromagnetic units or more and the resulting torque would be too large. If ferromagnetic material were used, one would have to shield well enough to reduce the field to less than 10^{-5} gauss, which is a much more difficult shielding problem. If on the other hand we use a non-ferromagnetic material of normal purity, it is highly unlikely that any ferromagnetic impurity in actual ferromagnetic form will be present at all, because the individual atoms of the impurity are not ferromagnetic and only micro-crystals of them are. In any case it is easy to check the rotor for residual ferromagnetism and reject it if it has a permanent moment exceeding 10^{-4} e.m.u., such as might result from iron particles imbedded in it. The ferromagnetic torque will then be less than 10^{-4} dyne-cm.

Induced current in the rotor will cause a parallel component or retarding torque only. The induced electromotive force will be about

$$10^{-8} \times 1 \times \pi\ (1.9)^2 \times 2\pi \times 1340 = 10^{-3} \text{ volts.}$$

The resistance of the rotor circuit is about 2.4×10^{-4} ohms and the inductance about 8×10^{-8} henries and the inductive reactance $8 \times 10^{-8} \times 2\pi \times 1340 = 6.7 \times 10^{-4}$ ohms. Consequently the current is about 1.4 amperes at a power factor of about 1/3. The power dissipated is then $1/2 \times 10^{-3} \times 1.4 \times 1/3 =$

2×10^{-4} watts. The corresponding retarding torque is 0.24 dyne-cm. This is tolerable, considering that it will occur only if the magnetic field is at the maximum allowable value and directed normal to the rotor axis, and that even then it will allow the rotor to coast for about three weeks.

The induced paramagneti moment is entirely negligible since the paramagnetic susceptibility is about 0.7×10^{-6} e.m.u./gm.

In all the above calculations the rotor material has been assumed to be aluminum alloy.

No further sources of parasitic torques are known.

4. Methods of Fabricating the Rotor

The rotor should be made in two halves with the joint in the equatorial plane, as shown in Fig. 1, because it would be difficult to make in one piece and because there is practic- ally no stress across the equatorial plane, so that the joint need not be as strong as the solid material.

The two halves may be either machined out of solid stock or drawn out of sheet material in a die and finish machined thereafter. Attention must be given to metallurgical problems such as direction of grain, if any, in the original stock and heat treatment, in order that the finished rotor have the full nominal strength of the hardened alloy and conform to the required shape within close tolerances, of the order of 0.1 mil,

and in order that it distort symmetrically when rotated at high speed. The mating halves of a rotor should be prepared from adjacent portions of the same piece of stock.

Two methods of making the joint suggest themselves: A series of spot welds around the ring or a series of rivets around the ring. Either of these methods would be acceptable provided the material is not distorted or weakened appreciably and provided the amount of material is controlled. Some sort of surface bond between the two mating surfaces of the halves of the ring would be preferable, but the writer does not know of any such technique for aluminum alloy.

5. Method of Sensing the Spin Axis

We have already indicated that the rotor geometry being proposed here permits electrical rather than optical sensing of the direction of the spin axis of the rotor, which is one of the advantages of the hybrid geometry. We have also already indicated that this electrical sensing is to be done by high frequency bridge circuits involving the electrodes a, b, c, etc. of Figure 2. Let the electrodes in the other half of the supporting envelope be called a', b', c', d', where a' faces a etc. (with the flat ring of the rotor in between, of course). Then we put the capacitance between a and c' into one arm of a bridge, and that between c and a' into the other

arm of the same bridge. The balance of this bridge will then be sensitive to an angular displacement of the rotor about an axis bd, but not to an angular displacement about an axis ac nor to any translational or linear displacement of the rotor. The unbalance voltage from this bridge may then be amplified and used to control a motor which rotates the supporting envelope about the axis bd. The motor can also drive a dial or revolution counter to indicate the angle about this axis to an accuracy of 1/10 minute of arc. A second bridge containing arms b, d' and d, b' with associated amplifier and motor can perform the same function with regard to axis ac.

The devices just described sense the geometrical axis of the rotor, whereas what we want to sense is the direction of the angular momentum vector of the rotor. These two directions do not necessarily coincide exactly, because the rotor may be turning about an axis slightly different from its geometrical axis. Now a freely rotating symmetrical body has the general property that the geometrical axis precesses about the (constant) direction of the angular momentum vector at a rate of $(C/A)\omega$ radians per second, where C is the moment of inertia about the figure axis and A is the moment of inertia about an axis through the center of mass normal to the figure axis. For the rotor here being discussed

$C = 58$ gm cm^2 and $A = 40$ gm cm^2. Hence the figure axis precesses about the angular momentum axis at $(58/40) \times 1340 = 1940$ cycles per second. If then the time constant of the servo loops is greater than say 1/100 second (it would be difficult to make it less since a mechanical motion is involved), this relatively high frequency oscillation will be averaged out and the envelope structure will point along the angular momentum vector as we want it to. In other words the rotor wobbles to a certain extent, but this wobble is at such a high frequency that it is averaged out by the servo loop.

In the previous paragraph we concluded that the frequency of the wobble is high enough so that it does no harm. What about the amplitude of the wobble? This amplitude is constant for the freely turning rotor, and its magnitude depends on the original conditions of accelerating the rotor to speed, in particular on how well the accelerating torque due to the rotating magnetic field was lined up with the rotor axis. This lineup can be made as good as one minute of arc by placing the accelerating coils accurately on the envelope structure. Thus we may count on a wobble amplitude not in excess of one minute of arc, which is quite harmless.

6. Bringing Rotor Up to Speed

We have already indicated that the rotor is first to be floated while not in rotation and then to be accelerated

up to 1333 r.p.s. by an induction motor type of torque, temporarily applied by means of a rotating magnetic field.

The rotor will presumably be lying on insulated supports before the suspending fields are turned on, and will be lifted off them and centered in the envelope when these fields are applied. At this point a problem arises because when the rotor is not turning it has no angular stability, certainly none from any of the machinery so far described. (This is quite different from the situation with the rapidly spinning rotor, which has a very high degree of angular stability.) Now it may be that when the rotor is lifted off its mechanical supports it will have a small enough angular velocity so that the servo system described in Section 5 can follow it until the rotor acquires enough angular momentum to stabilize it; we cannot be sure of this. If not, then we must temporarily disconnect the two servo amplifiers of Section 5 from the motors and let them control some supporting electric fields temporarily applied to the electrodes a, a', b, b' etc. to give the rotor angular stability until it is accelerated. Once the rotor has been accelerated, these auxiliary supporting fields must be turned off and the servo amplifiers returned to their normal function of driving motors which make the envelope follow the rotor axis.

The next and last item to be discussed in this section

is the rough design of the accelerating coils. These coils must supply a rotating magnetic field rotating at a speed higher than the design rotor speed, say at 2000 revolutions per second, and of sufficient strength to bring the rotor up to speed in a reasonable time. Assume that we allow 1000 seconds for this process; then the torque must be

$$\frac{4.9 \times 10^5}{10^3} = 490 \text{ dyne-cm.}$$

Now by the same type of calculations as those relating to parasitic torques in stray magnetic fields, we find that this torque will be produced on the rotor by a field of about 30 gauss. Incidentally, there will be a certain amount of joule heating of the rotor during the accelerating process, because there will be about 40 amperes circulating in the rotor. The joule heating will be about 0.5 watts, or 120 calories for the 1000 second period, which will cause the rotor temperature to rise 40° centigrade. We mention this because the rotor has very poor thermal contact with its surroundings and must not be overheated in the accelerating process.

The coils may be two circular coils about 3" in diameter in two perpendicular planes containing the axis of the system, and fed in quadrature. In order to produce 30 gauss at the center there must be 180 ampere turns.

Suppose the coils consist of 540 turns of No. 30 wire. Then the resistance of each coil will be 43 ohms and its reactance at 2000 cycles will be 1000 ohms, and 330 volts will have to be applied to it in order to produce the required accelerating field. By means of a resonating capacitance, we can increase the impedance to about 20,000 ohms, which is convenient for vacuum tube drive.

7. Suggested Initial Development

It is possible to investigate the practical feasibility of this type of free gyro navigation system and to establish the attainable accuracy of such a system without having to construct a complete navigation apparatus. The essence of the question which must be answered practically is: how accurately will the rotor axis remain stationary relative to the fixed stars for arbitrary orientations of this axis relative to the vertical?

We may answer this question by building a single working model of a free gyro, rather than a pair which would be required for a navigation apparatus, and operating it as a free gyro clock. By a free gyro clock we mean a freely rotating body with its spin axis pointing normal (or at least not parallel) to the earth's polar axis, and kept in a fixed location on the earth. The spin axis should then of course turn about the polar axis through precisely one revolution

per sidereal day. The supporting frame can be driven at precisely this rate about an axis accurately parallel to the earth's polar axis by a chronometer and the discrepancies observed and tabulated by a human operator. The supporting servo circuits would have to be complete, but the axis-sensing servo loops would not have to be closed for this type of test.

Thus the construction of a free gyro clock would involve less than half the apparatus required for a complete navigation system. In spite of this, the free gyro clock development can readily provide actual operating performance figures for the rate of drift of the spin axis for all orientations relative to the vertical, that is to say, all the relevant performance information for a free gyro.